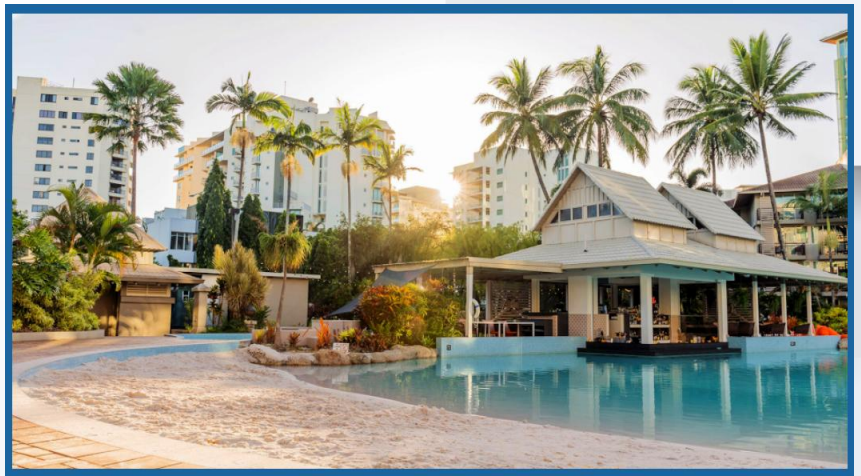


Fundamental Problems in Subatomic Physics 2026

大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex

Experimental studies for hyperon bound systems at the J-PARC K1.8 beam line

T.O. Yamamoto
(Japan Atomic Energy Agency, J-PARC)

Contents

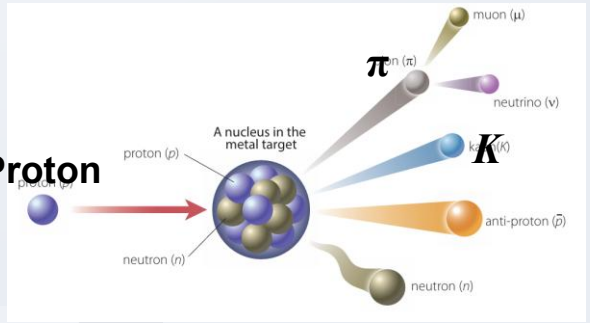
- Experiments for hyperon-bound systems at the J-PARC K1.8 beamline
  → study of hyperon-nucleon interaction
  - Experiments for S=-1 systems
  - Experiments for S=-2 systems
- Future prospects
- Summary

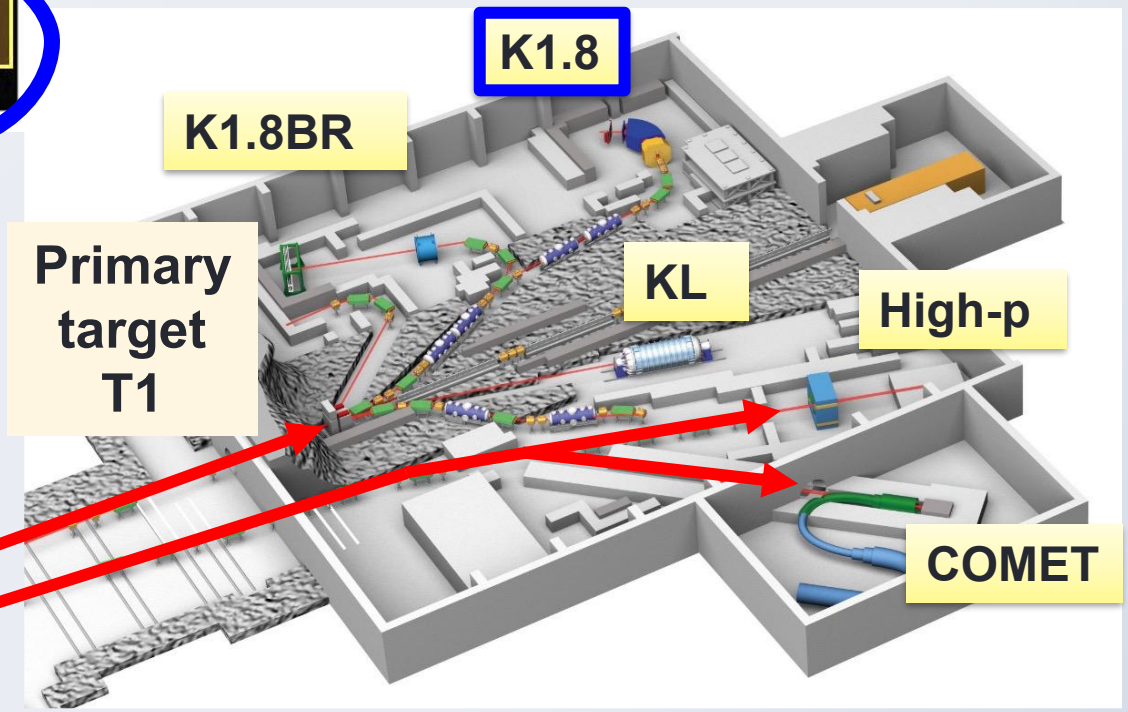
Hadron Experimental Facility



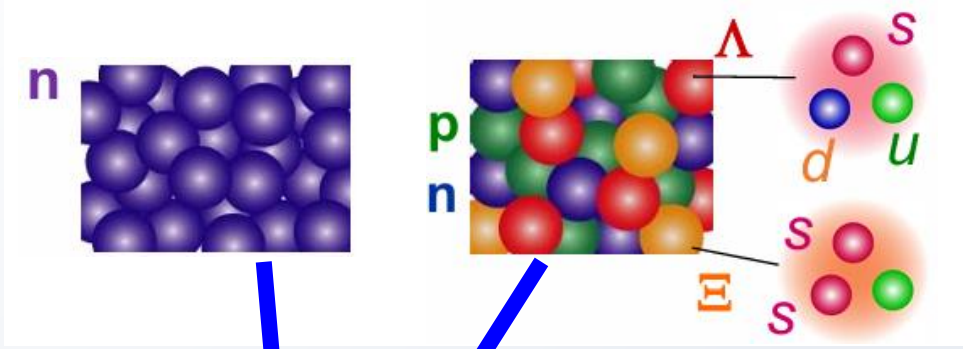
Primary and Secondary beamlines for

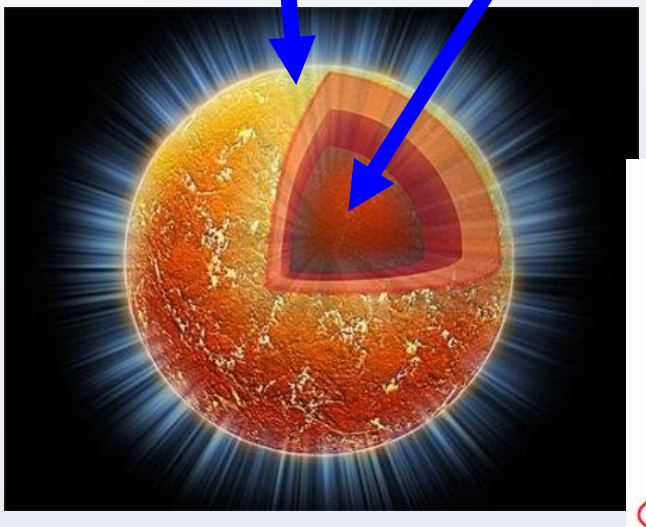
- ***Strangeness nuclear physics***
- ***Hadron physics***
- ***Flavor physics***





Neutron star and hyperons

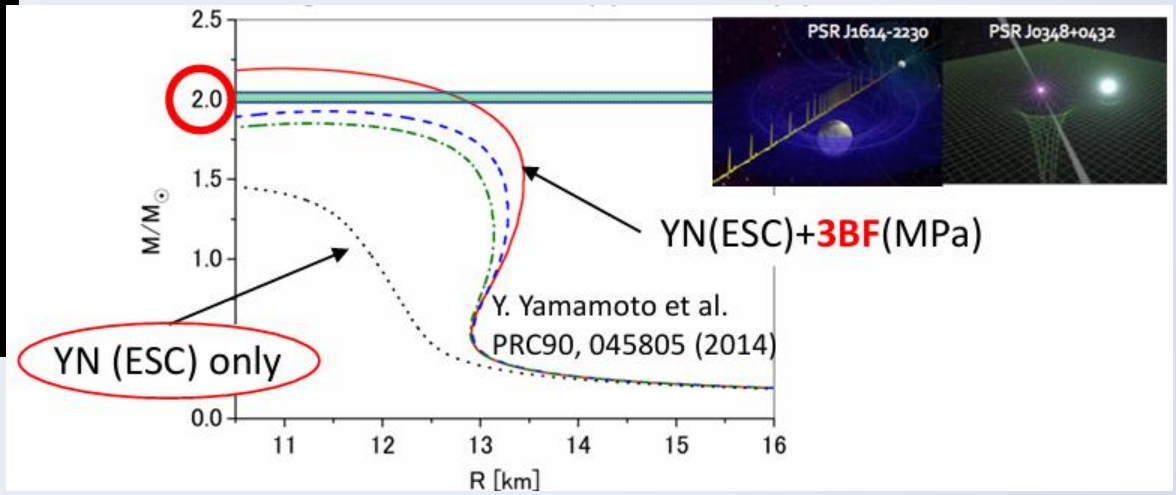




Hyperons (Y) should appear in high-density conditions

"Hyperon puzzle"

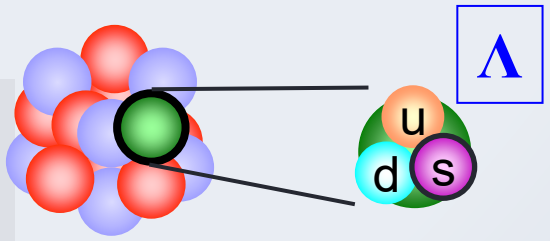
Softening of EOS w/ hyperon appearance



Knowledge of Hyperon-Nucleon interaction is essential to understand structure of neutron stars.

Experiments for Strangeness = -1 system

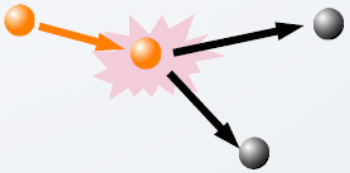
Λ hypernucleus



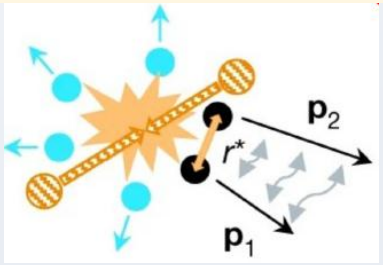
Hyperon–nucleon (YN) interaction

Baryon-Bryon interaction

Scattering exp.

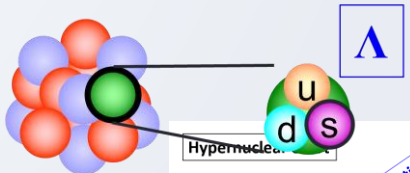


Two particle correlation

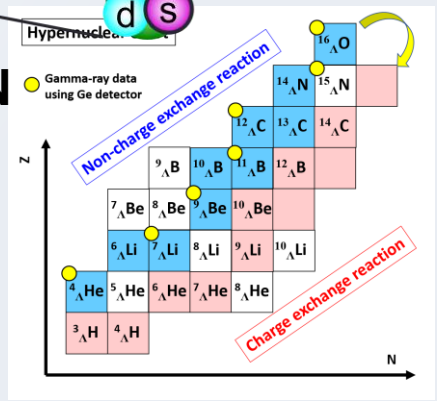


Light Λ,Ξ hypernuclei

Λ hypernucleus

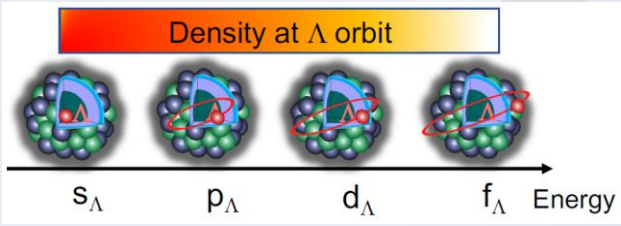


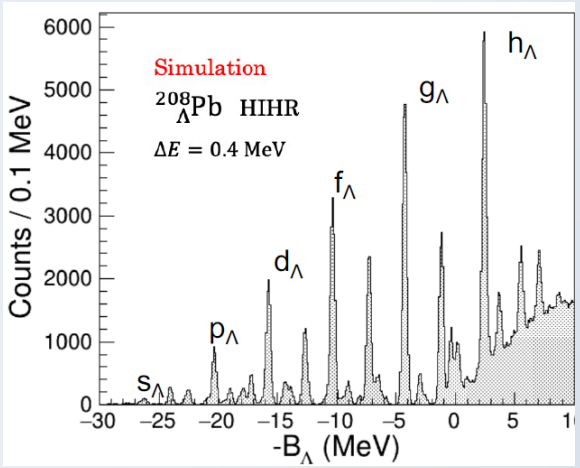
ΛN⇔ΣN



Reaction/Gamma-ray spectroscopy

Heavy hypernuclei



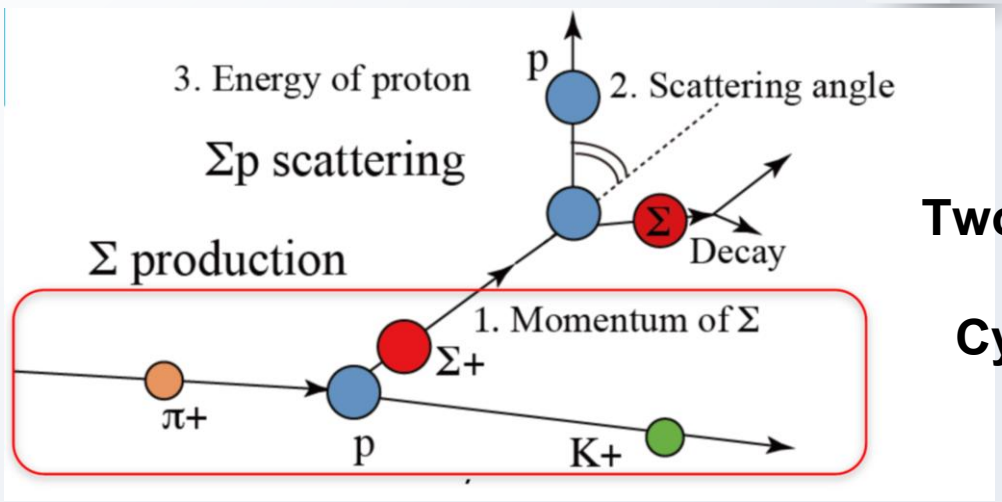


Two-body Hyperon-Nucleon (YN) int.

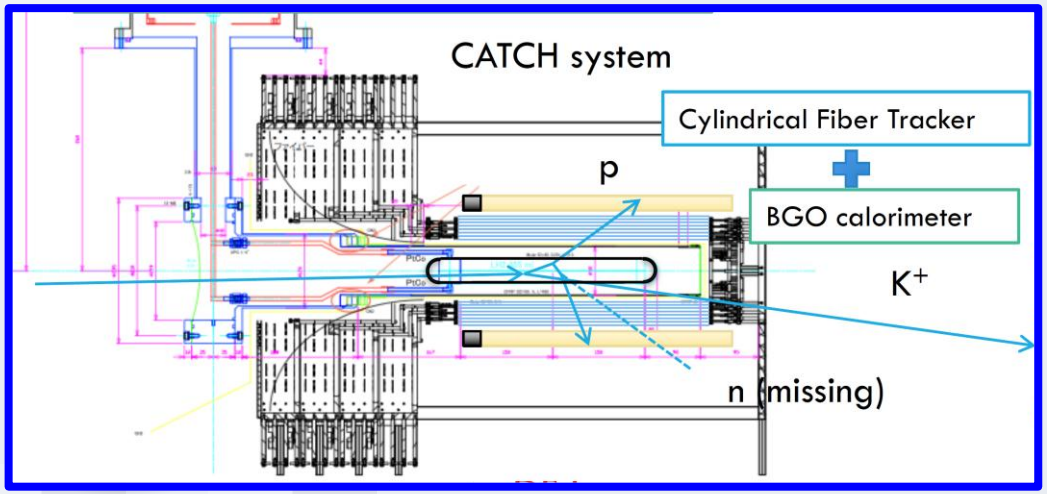
Baryon mixing in medium, YNN int.

Density dependent int. ⇒ Neutron star

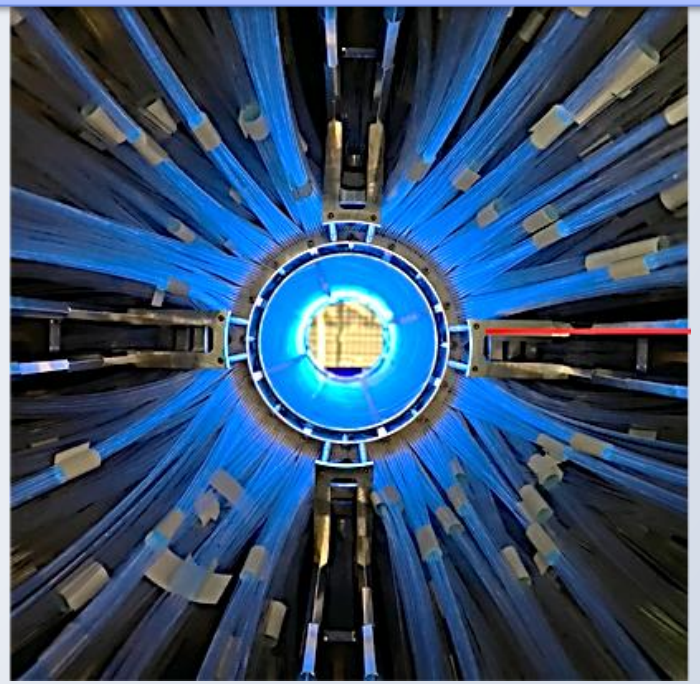
ΣN scattering experiment (E40)



Two-step process in the liq. H2 target
+
Cylindrical detectors (fiber + BGO)

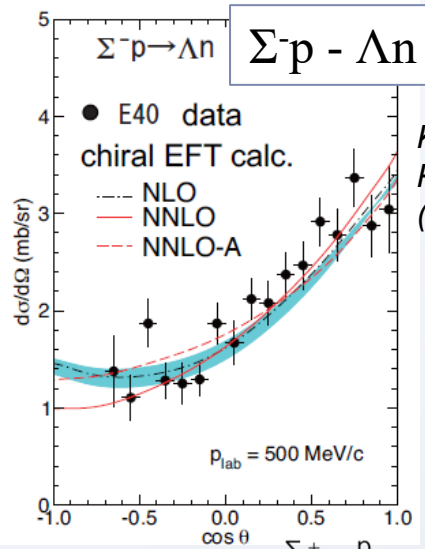


Cylindrical Fiber Tracker (CFT)



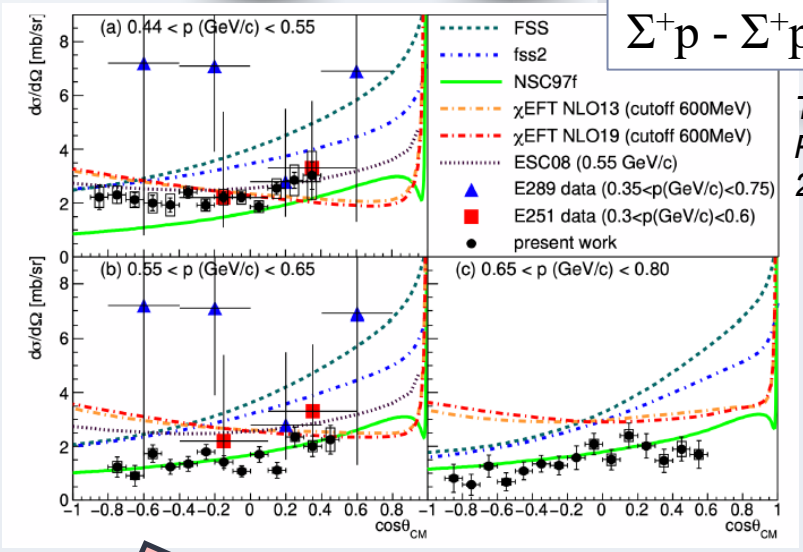
A fiber detector allows the use of a high-rate beam (~10 MHz)

ΣN scattering experiment (E40)



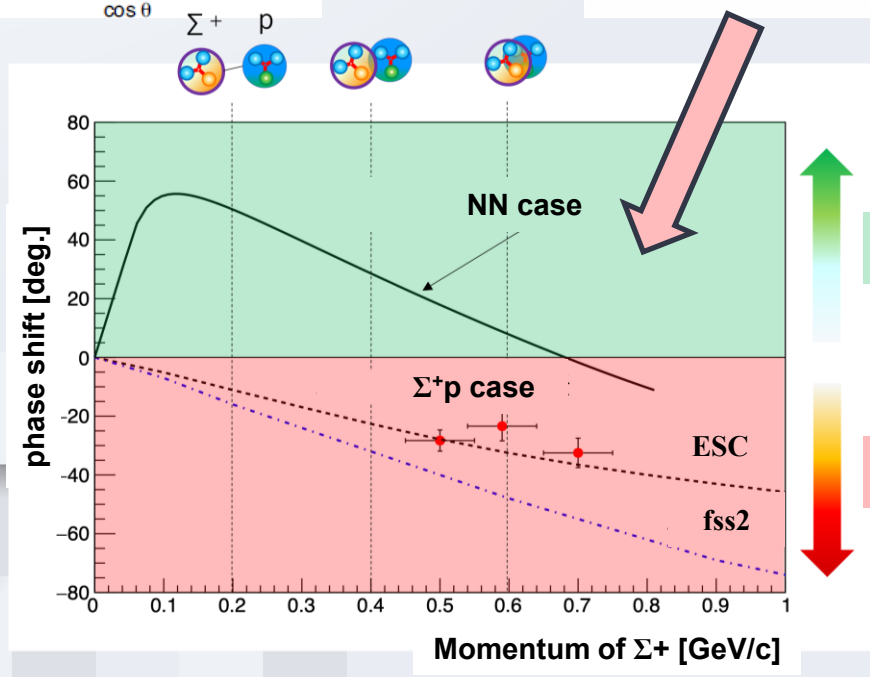
Σ⁻p - Λn

K. Miwa et al., PRL 128, 072501 (2022)



Σ⁺p - Σ⁺p

T. Nanamura et al., Prog. Theor. Exp. Phys. 2022 093D01



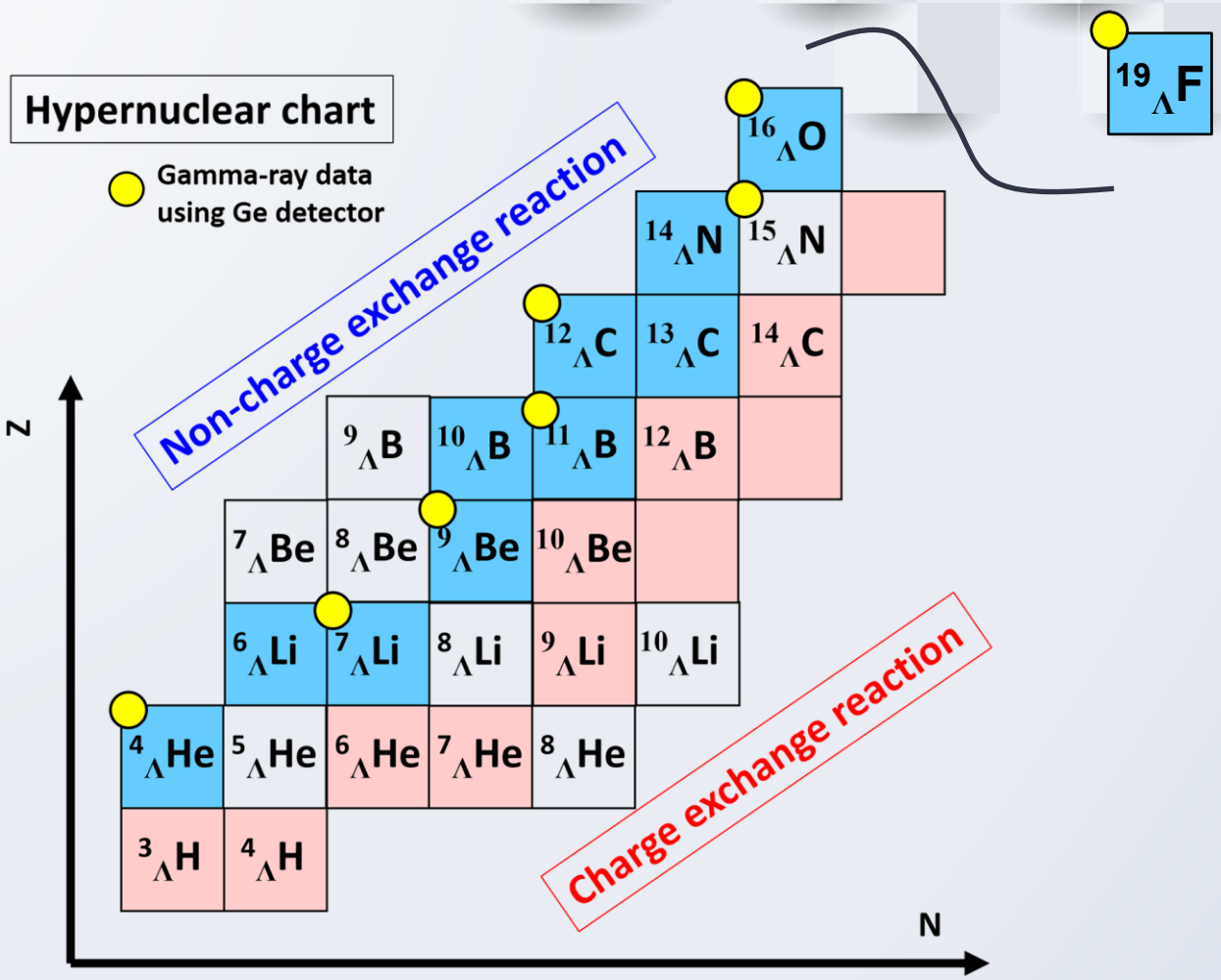
attractive

repulsive

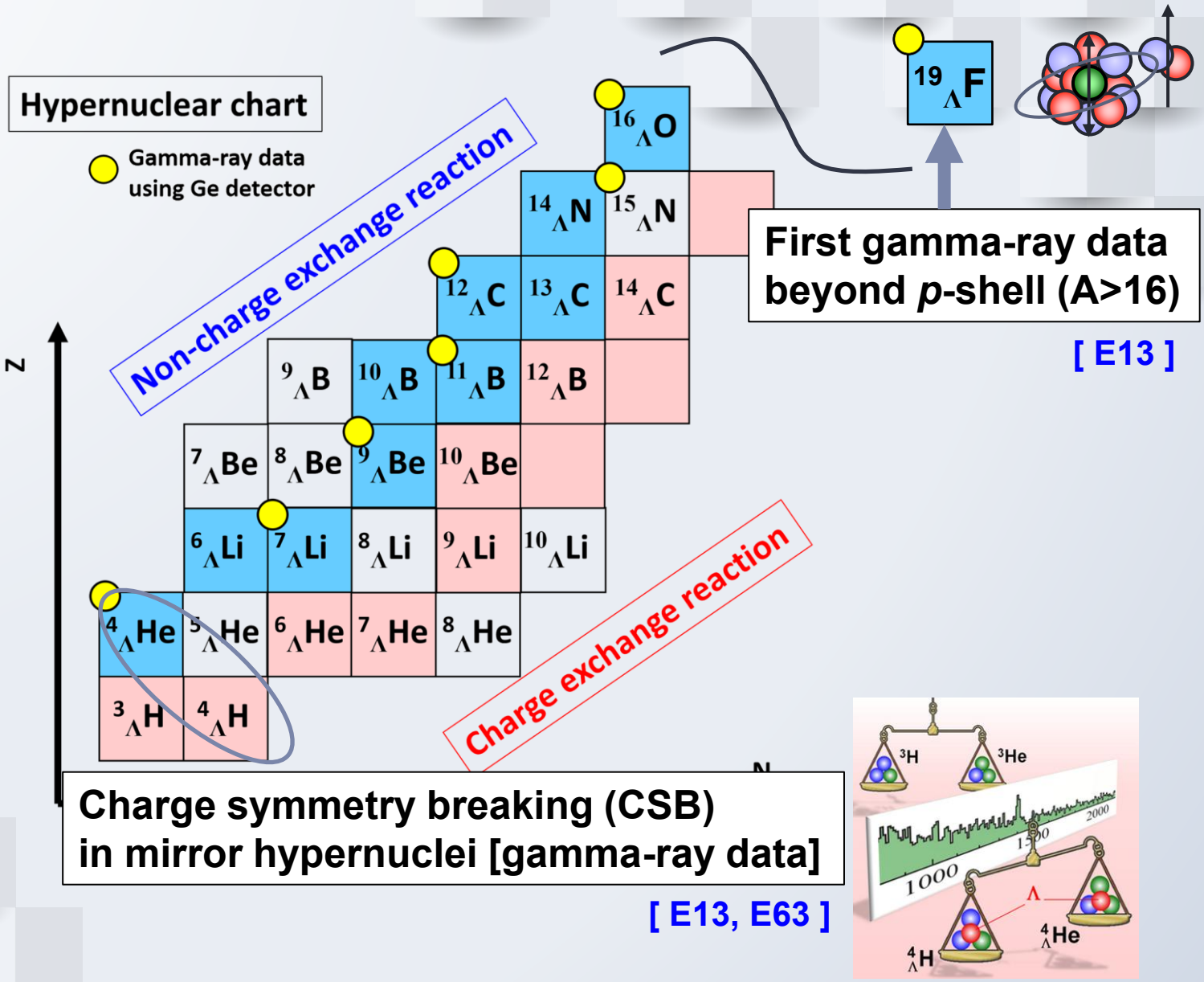
We reported phase shift and repulsive strength

[future (ongaing)] New measurements with the CATCH system for ΛN scattering.

Λ hypernuclei studied in J-PARC



Λ hypernuclei studied in J-PARC



First gamma-ray data beyond *p*-shell (A>16)

[E13]

Charge symmetry breaking (CSB) in mirror hypernuclei [gamma-ray data]

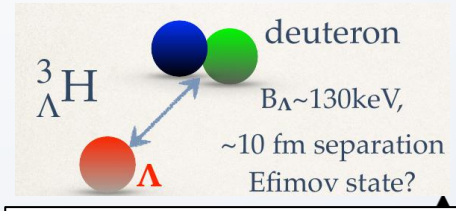
[E13, E63]

Λ hypernuclei studied in J-PARC

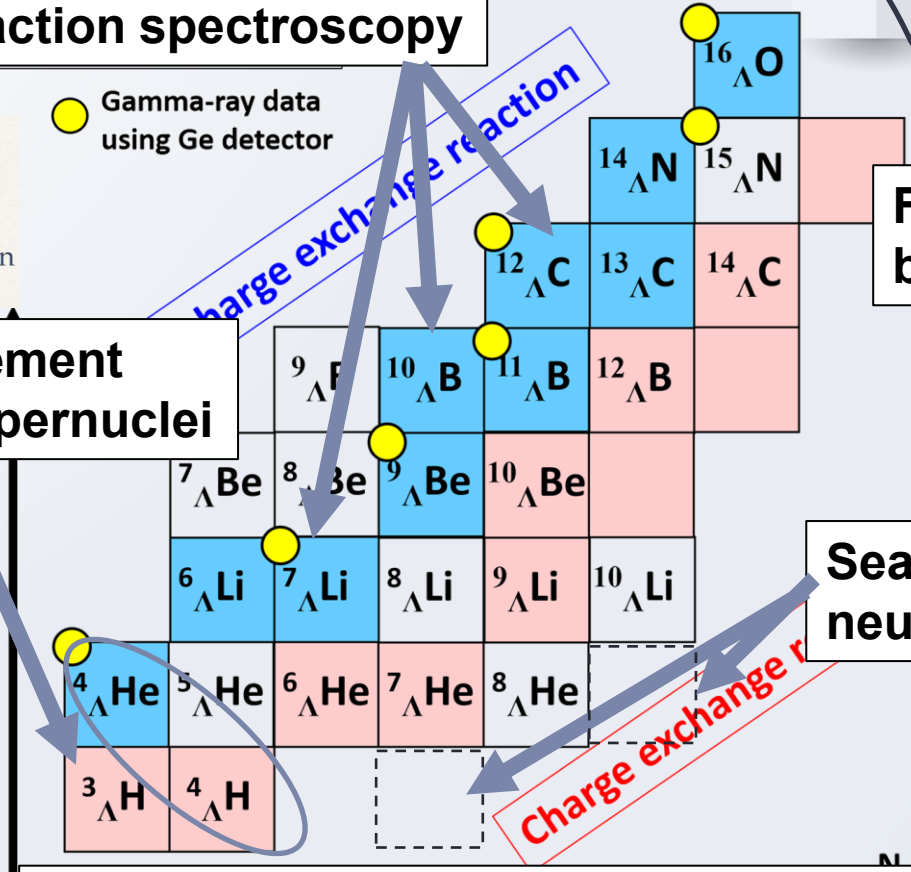
High-resolution reaction spectroscopy [E94]

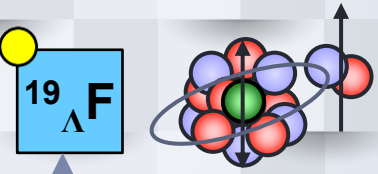
Gamma-ray data using Ge detector

Charge exchange reaction



Lifetime measurement of the lightest hypernuclei [E73]

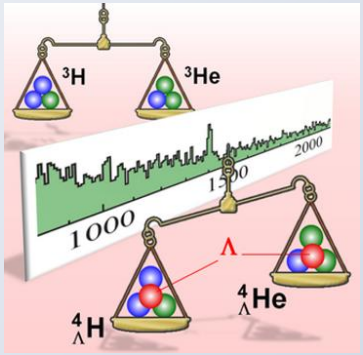




First gamma-ray data beyond *p*-shell (A>16) [E13]

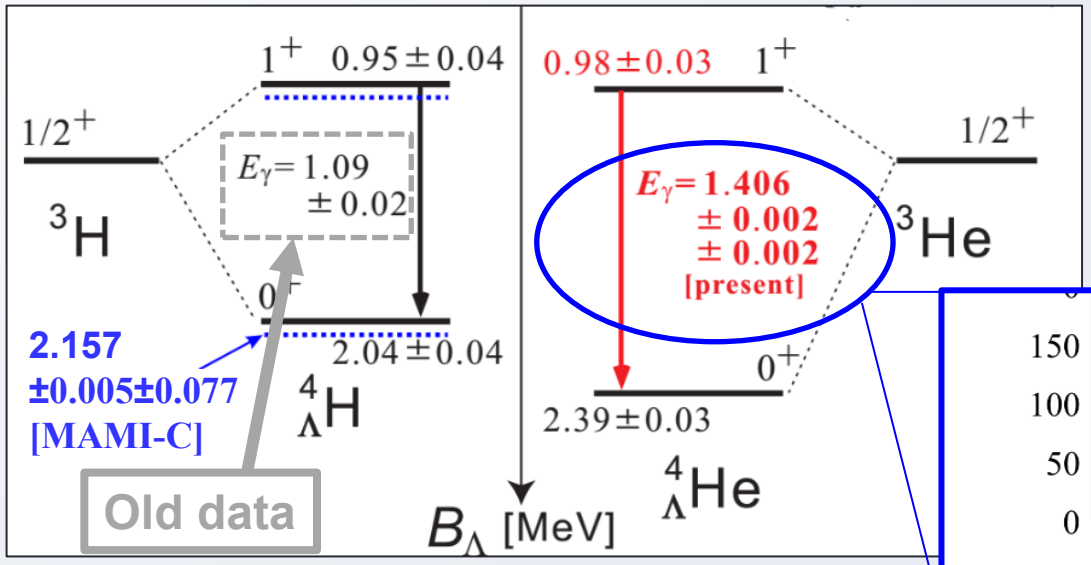
Search for neutron-rich hypernuclei [E10]

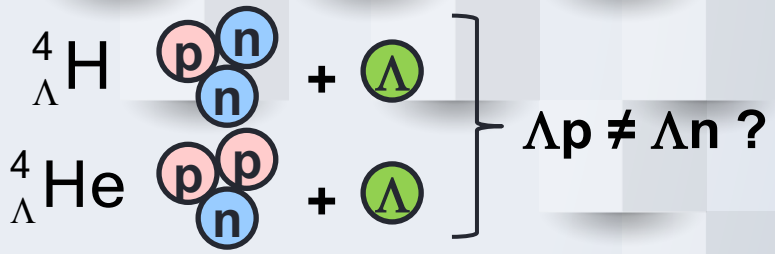
Charge symmetry breaking (CSB) in mirror hypernuclei [gamma-ray data] [E13, E63]



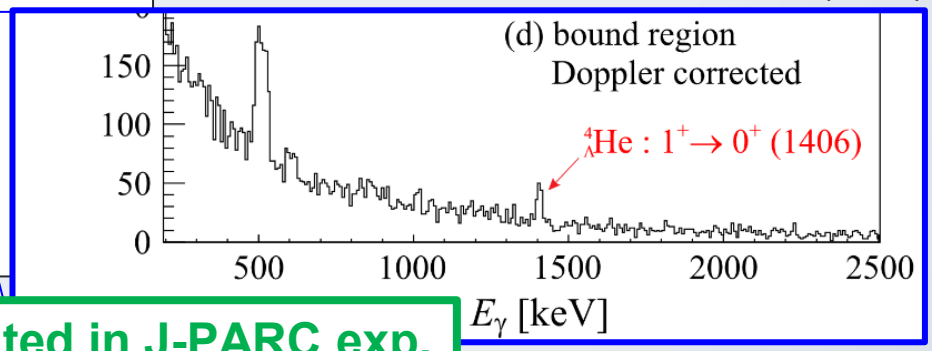
Ofservation of CSB effect in hypernuclei

Level schema of mirror A=4 hypernuclei





T. O. Yamamoto et al., Phys. Rev. Lett. 115, 222501 (2015)



Updated in J-PARC exp.

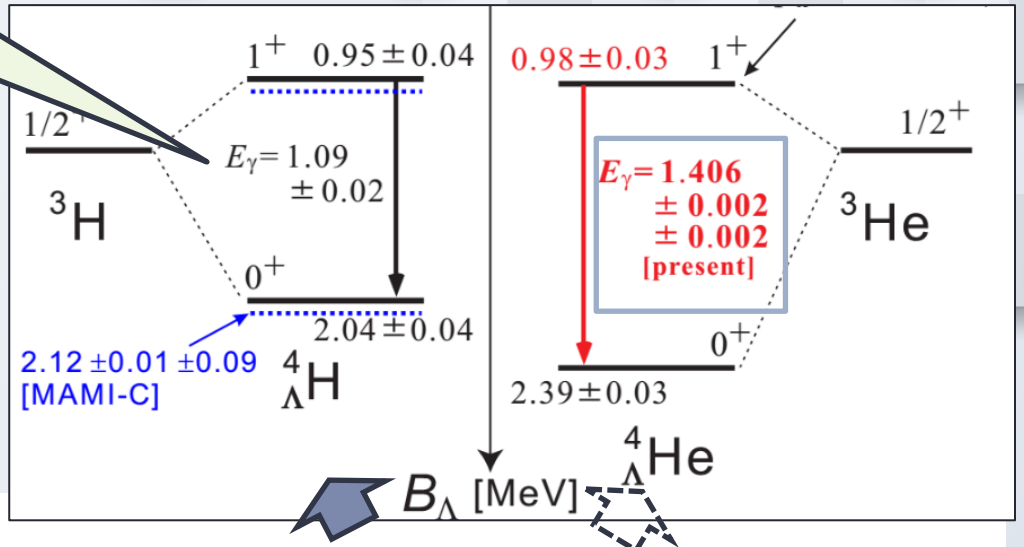
Existence of Charge symmetry breaking (CSB) in A=4 system was confirmed by gamma-ray spectroscopy using Ge detector array, Hyperball-J.

- **~0.3 MeV difference in excitation energy.**
  -> Spin dependent CSB effect?
- **ΛN-ΣN mixing may play important roll?**

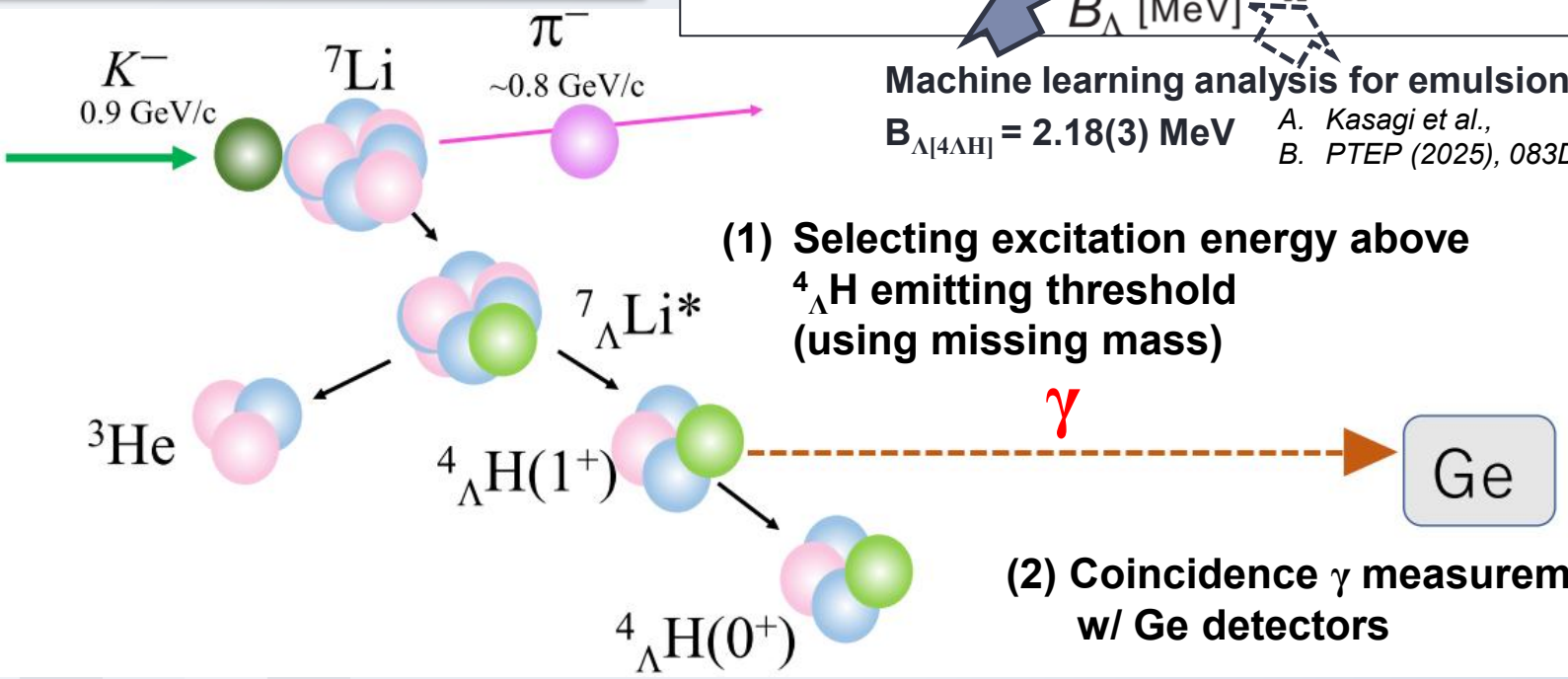
New measurement for $^{4}_{\Lambda}$H gamma-ray

Old data using NaI detector

New experiment
[J-PARC E63 started from 2025]
Precise data using Ge detector



Secondary hypernuclei method



Machine learning analysis for emulsion exp.

$B_{\Lambda[4\Lambda H]}$ = 2.18(3) MeV

A. Kasagi et al., B. PTEP (2025), 083D01.

(1) Selecting excitation energy above $^{4}_{\Lambda}$H emitting threshold (using missing mass)

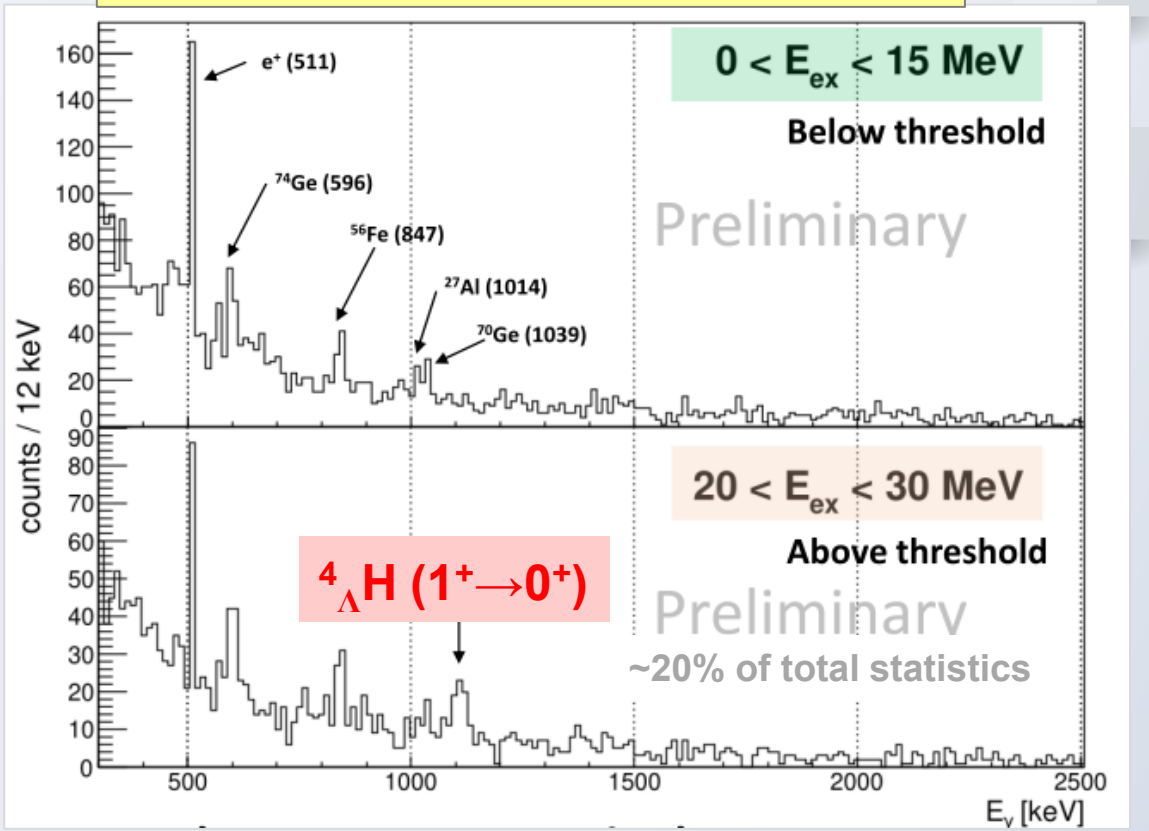
(2) Coincidence γ measurement w/ Ge detectors

New measurement for $^{4}_{\Lambda}$H gamma-ray

Ge detector array: Hyperball-XX



Gamma-ray energy spectra [2025 data]



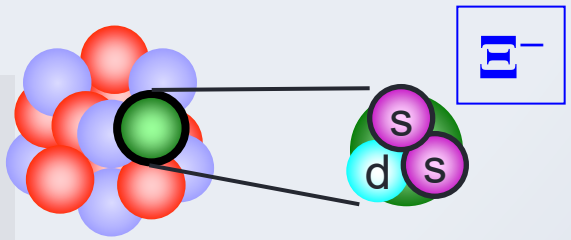
$^{4}_{\Lambda}$H peak @1.1 MeV is observed even with the present statistics

<5 keV accuracy is expected w/ full statistics (in 2026 run)

→ Excitation energy for both $^{4}_{\Lambda}$H / $^{4}_{\Lambda}$He will be fixed by solid data.

Experiments for Strangeness = -2 systems

Ξ hypernucleus



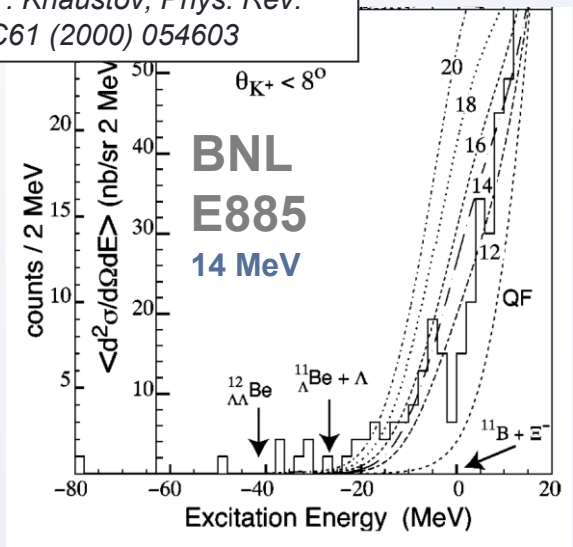
$K^-(s\bar{u})$ beamline is essential.

Reaction spectroscopy of Ξ hypernuclei

(K^-, K^+) reaction spectroscopy experiments are flagship experiments at the J-PARC HEF K1.8 beamline.

J-PARC experiments

P. Khaustov, Phys. Rev. C61 (2000) 054603



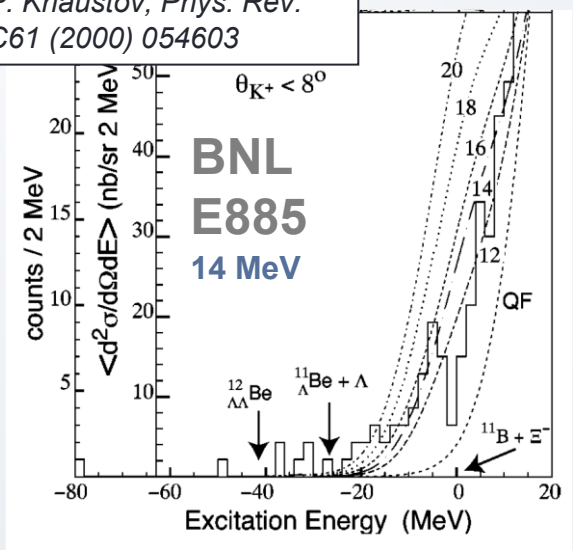
No clear peak structure for bound states

	KEK E224	BNL E885
Resolution FWHM (MeV)	22	14

Reaction spectroscopy of Ξ hypernuclei

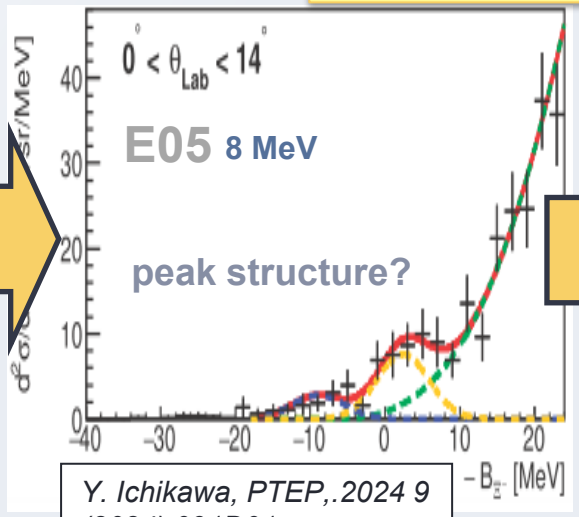
(K^-, K^+) reaction spectroscopy experiments are flagship experiments at the J-PARC HEF K1.8 beamline.

P. Khaustov, Phys. Rev. C61 (2000) 054603

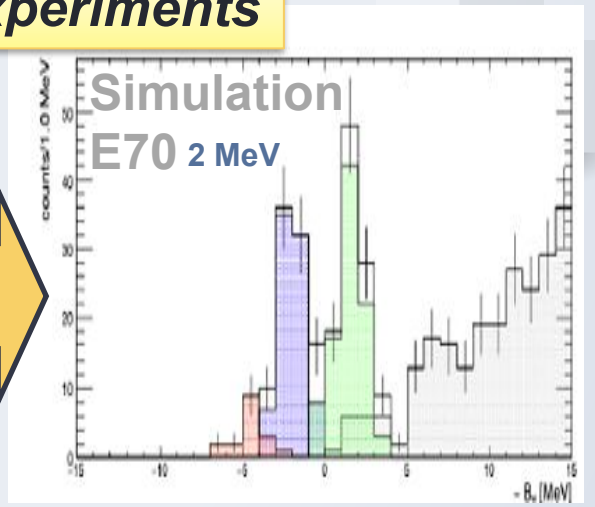


No clear peak structure for bound states

J-PARC experiments



Y. Ichikawa, PTEP,.2024 9 (2024) 091D01

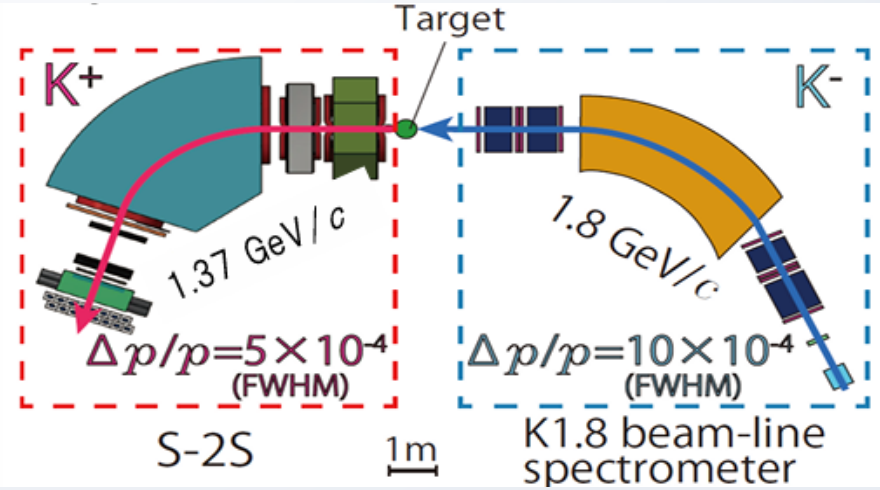


We expect observation of peak structure In next measurement

	KEK E224	BNL E885	J-PARC E05	J-PARC E70
Resolution FWHM (MeV)	22	14	8	2

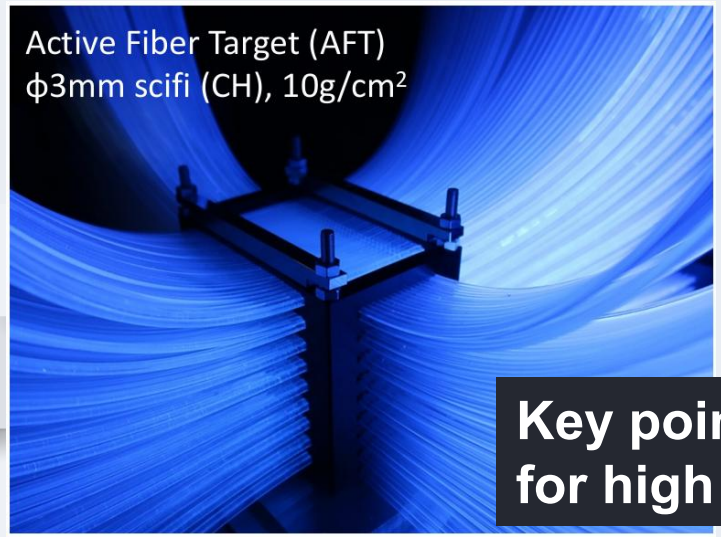
Spectroscopy of Ξ hypernuclei (E70)

High-resolution spectrometer (S-2S) was constructed in 2023.
Commissioning and data-taking were performed (2023-2025).



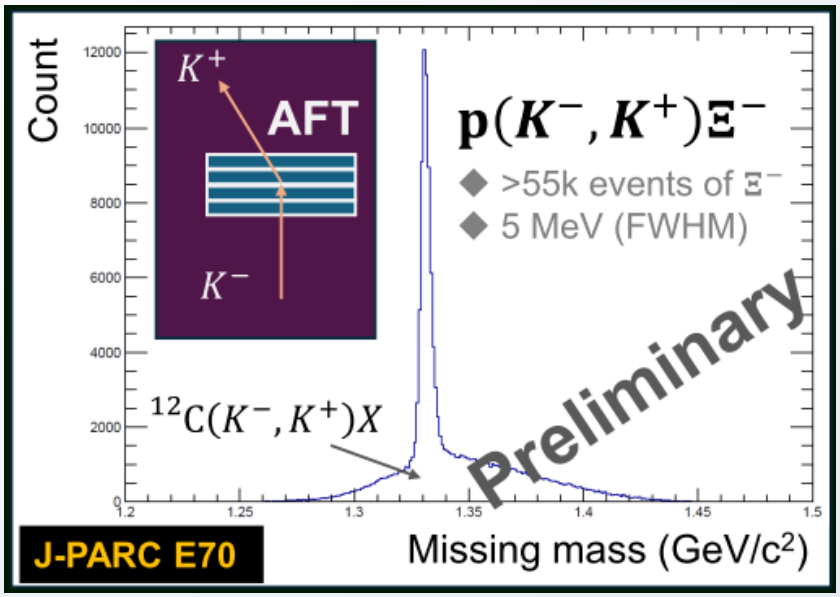


Key point ①
for high resolution

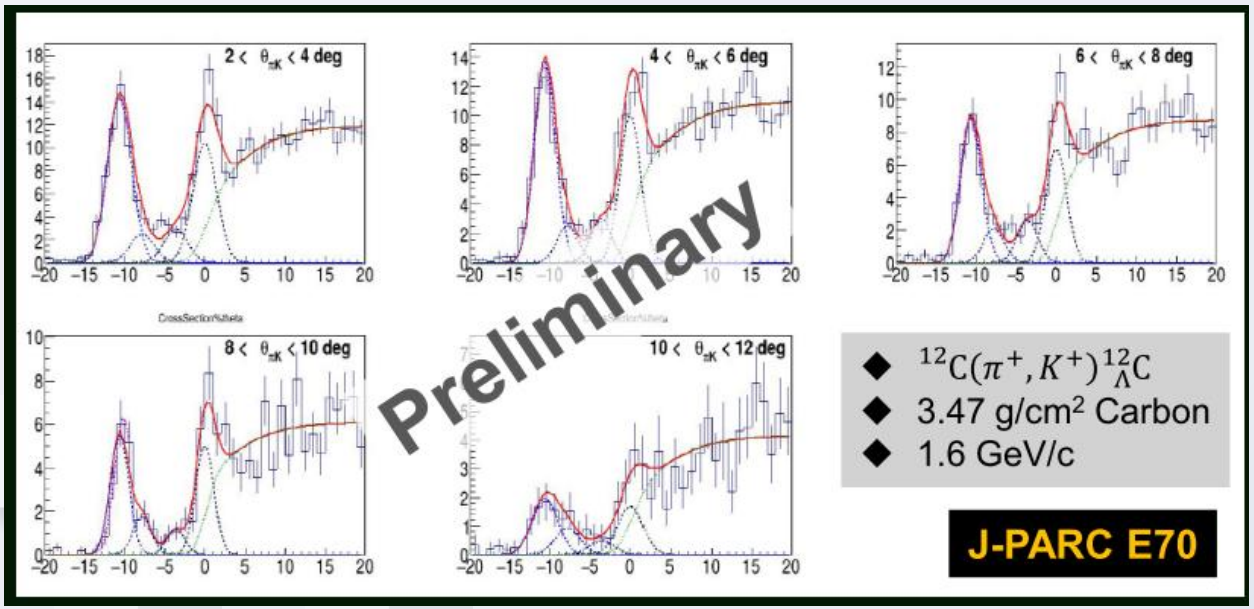


Key point ②
for high resolution

Spectroscopy of Ξ hypernuclei (E70)



- 350G kaons irradiated on the target.
  (x4 of the previous E05)
- Analysis is on-going
  * x2 better resolution than E05 so far.
  * We are making effort to achieve
    the designed resolution
    (x4 better than E05)



[Byproduct]
New cross-section data:
$^{12}_{\Lambda}$C via the (π^+,K^+)
@1.6 and 1.8 GeV/c

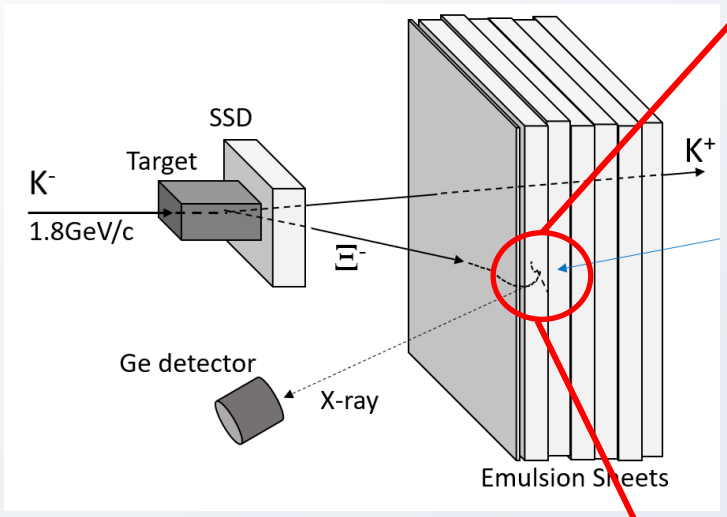
(preparing for the publication)

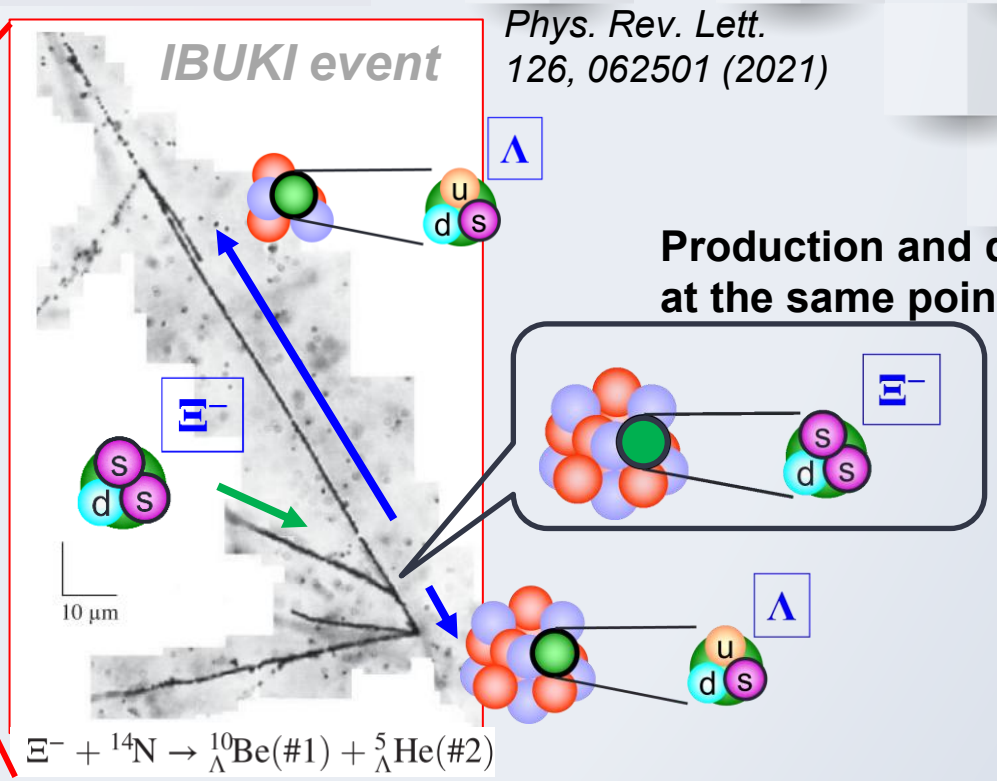
Search for Ξ bound system w/ Emulsion

Done in J-PARC E07

Emulsion image in Ξ nuclear absorption

S.H. Hayakawa et al., Phys. Rev. Lett. 126, 062501 (2021)



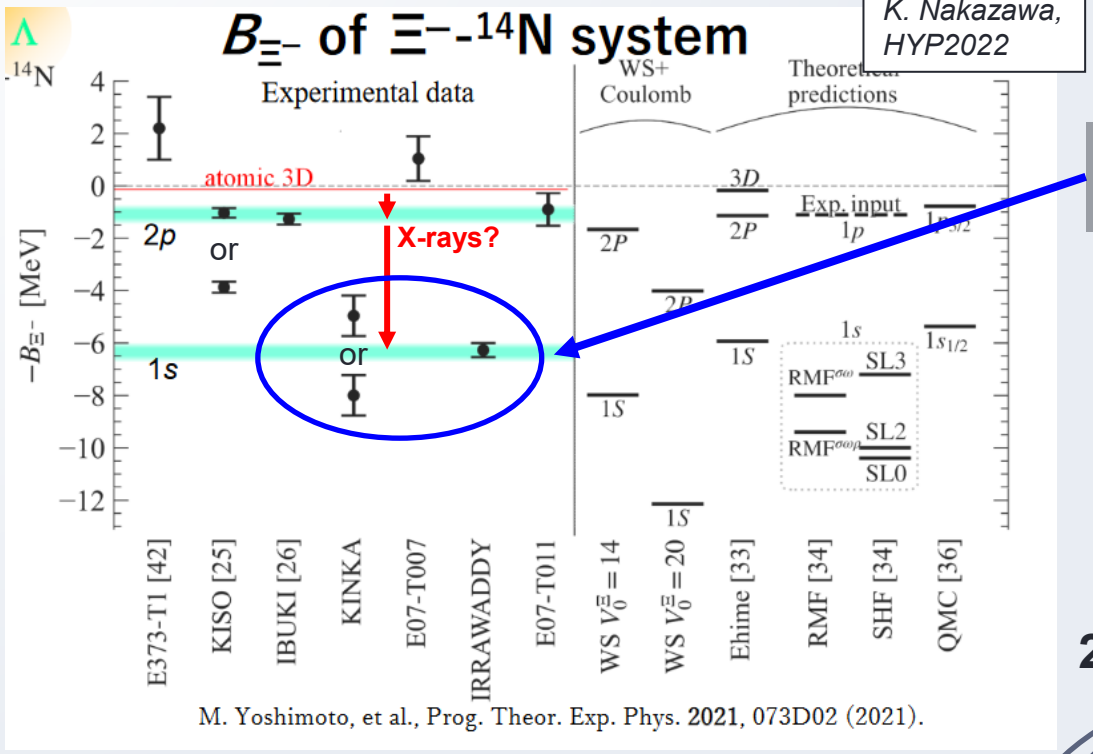


"Hybrid method"
SSD tracking
+ Track following in emulsion

- **Many "Ξ bound state → twin Λ hyper nuclei" events were found.**
- **Binding energy of "Ξ bound states" was measured from track length/direction.**

Search for Ξ bound system w/ Emulsion

Done in J-PARC E07



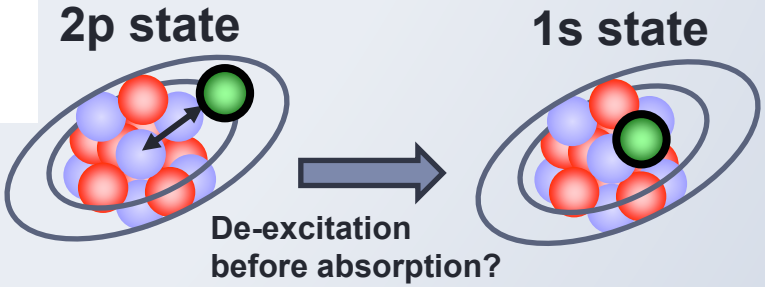
M. Yoshimoto, et al., Prog. Theor. Exp. Phys. **2021**, 073D02 (2021).

K. Nakazawa, HYP2022

Surprising

Observation of 1s state suggests very weaker absorption than prediction.

Small ΞN→ΛΛ conversion?
Effect of Ξ^-p-Ξ^0n mixing?



Special events found in J-PARC E07



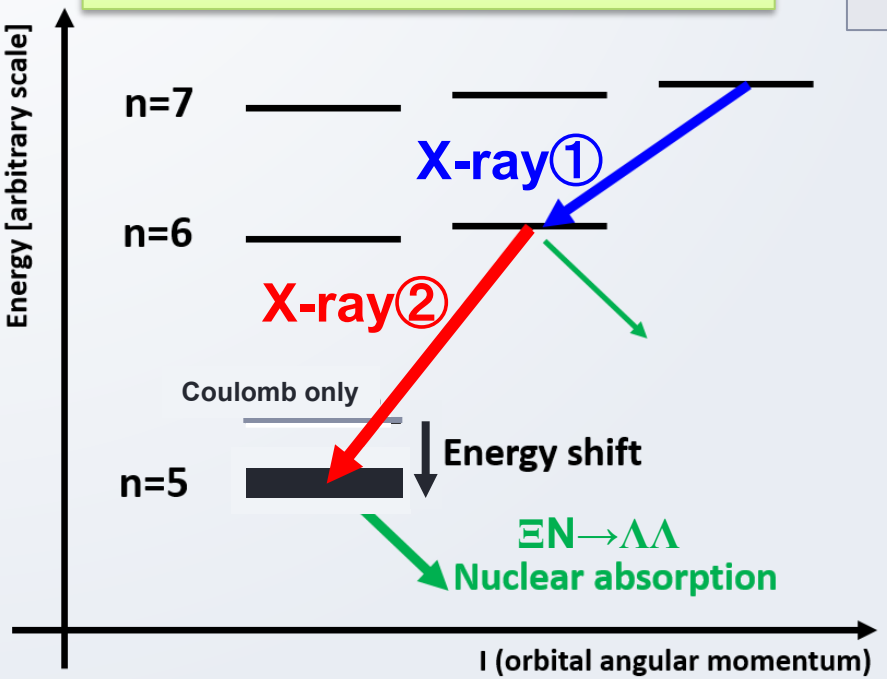


IRRAWADDY event

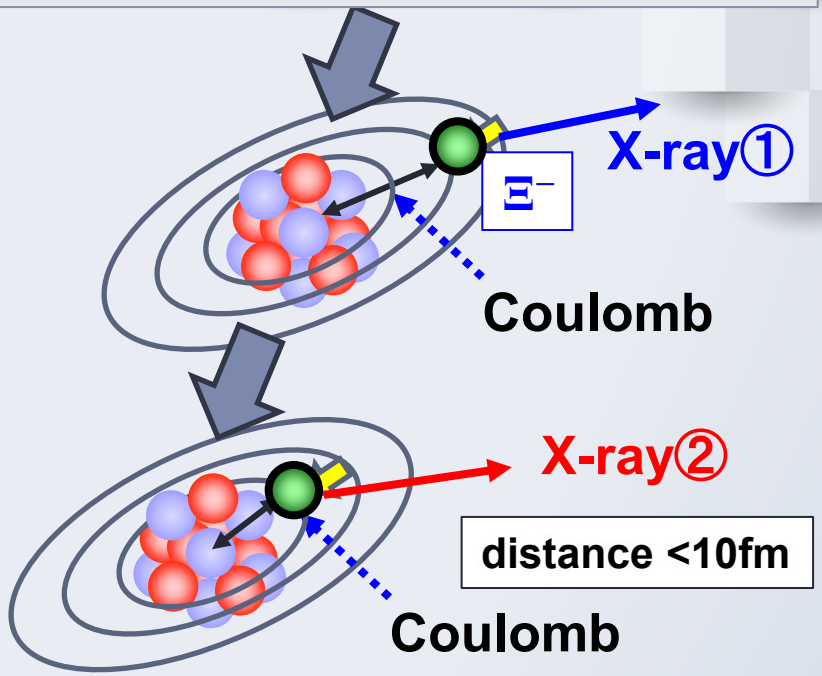
→ **Need father statistics**
(automated scan method)
and X-ray data

X-ray spectroscopy of Ξ⁻ atom

Level scheme of Fe-Ξ⁻ atom



Ξ⁻ stops in matter→ formation and de-excitation of Ξ⁻ atom



Measurement of energy shift and width
→ Ξ⁻A real and imaginary terms (near surface)

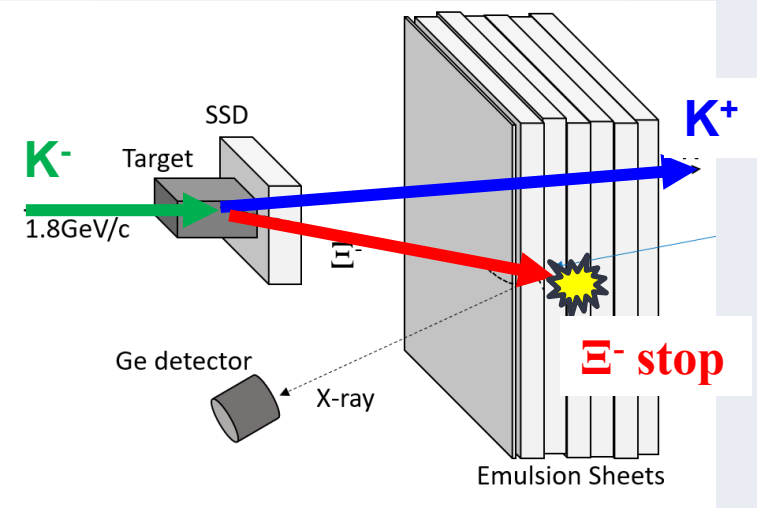
We are aiming at world first measurement of X ray from Ξ⁻-atom

X-ray spectroscopy: 1st and 2nd try

Technical difficulties:

- Low yield rate (K^- beam intensity x cross-section)
- High Ξ^- momentum (~0.5 GeV/c) for the (K^- ,K^+) reaction
  → Large decay prob. (BG) & Low Ξ stop prob. (Signal, forming Ξ atom)

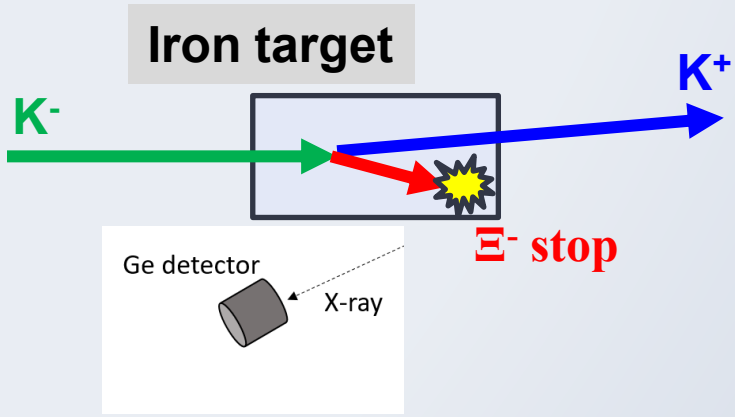
Emulsion method [E07]



GOOD **Stop ID w/ emulsion (good S/N)**

BAD **Limited yield due to emulsion**

High density target method [E03]

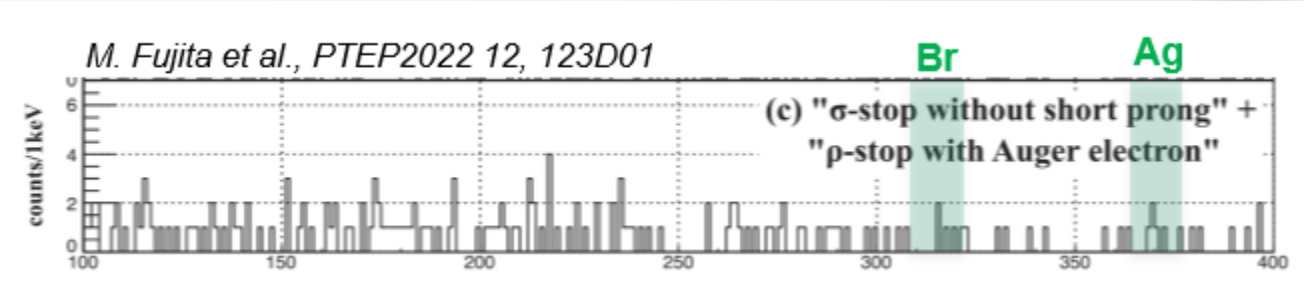


GOOD **High yield rate**

BAD **No direct stop ID (bad S/N)**

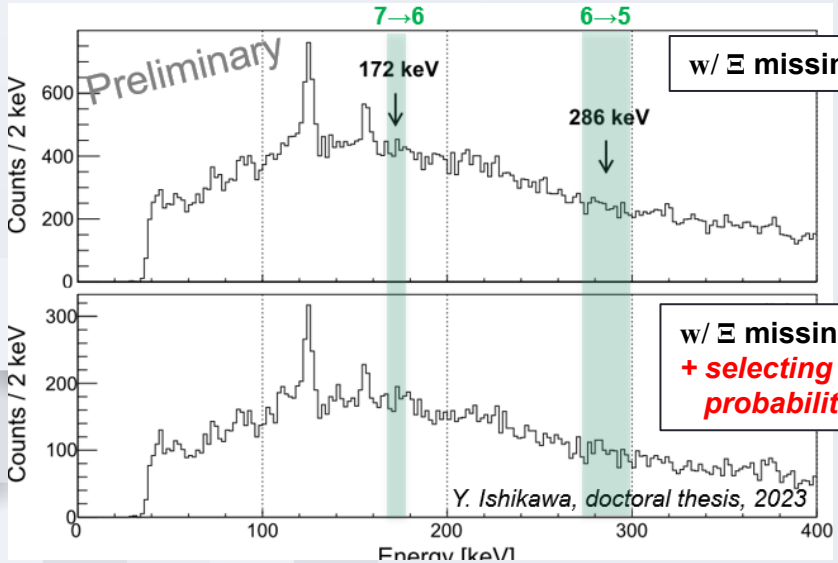
X-ray spectroscopy: 1st and 2nd try

Emulsion method [E07] **for Ag, Br-atom inside emulsion**



Not enough statistics due to limitations from the emulsion

High density target method [E03] **for Fe-atom**



Upper limit for X-ray-emitting prob. = 0.19

- **BG level: as expected**
- **X-ray yield may be smaller than expected**

Effect of Ξ^-p-Ξ^0n mixing? (in N and Fe cases)

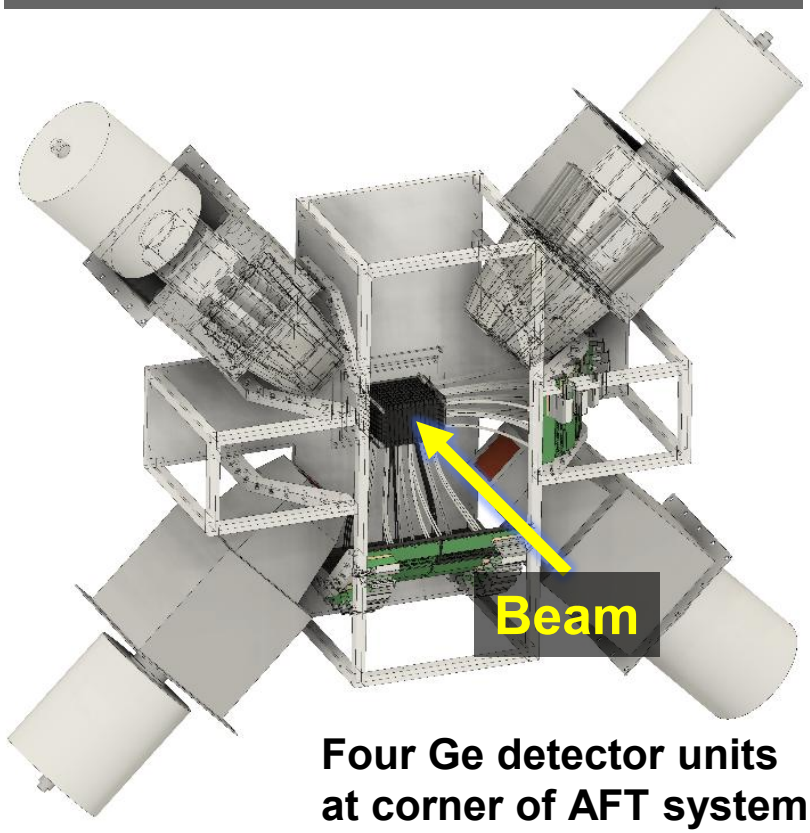
X-ray spectroscopy: on-going exp.

Stop ID using AFT [E96]



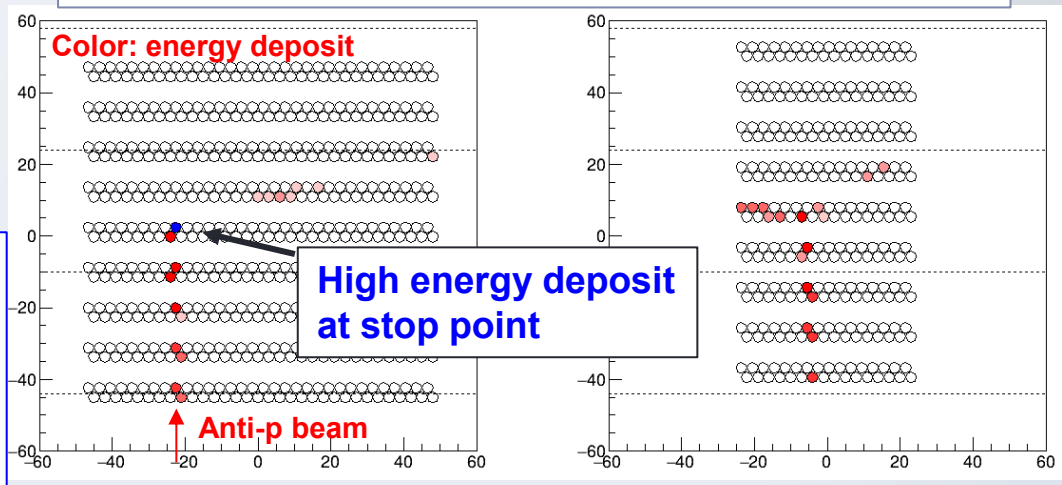
Balance of yield and S/N

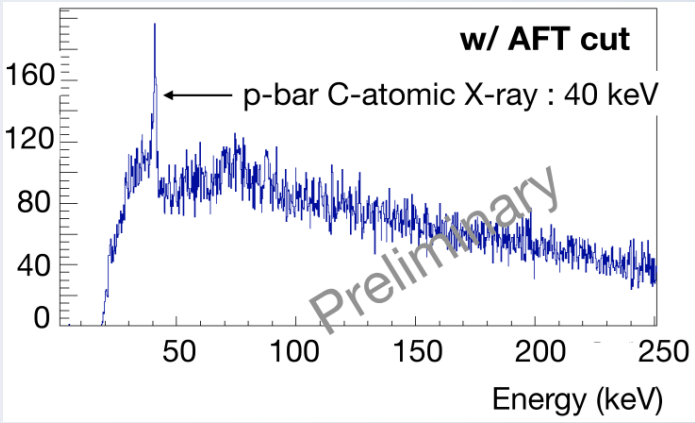
Ge detector array Hyperball-X



Four Ge detector units
at corner of AFT system

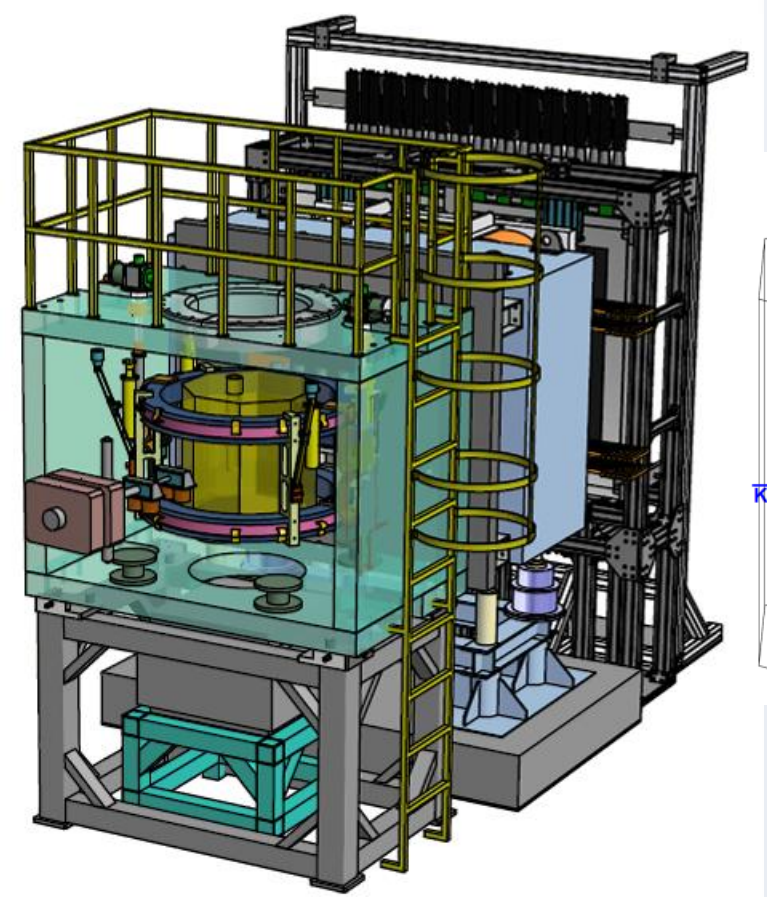
Event display for anti-proton beam data



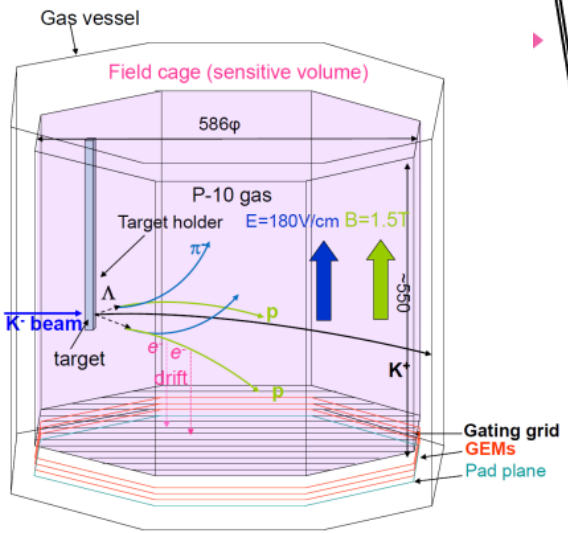


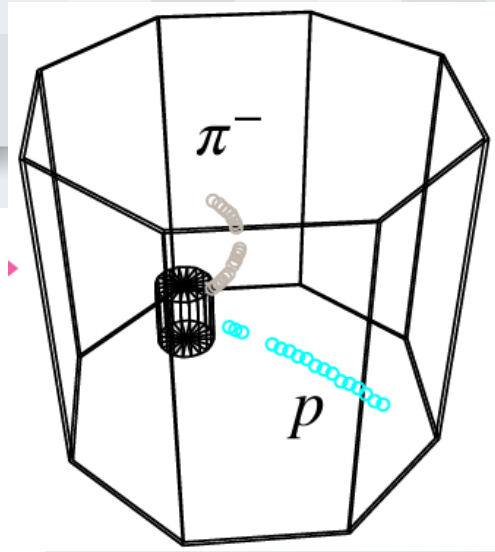
Data-taking was finished in 2025.
Analysis (AFT hit image) is ongoing

Experiments with HypTPC @K1.8



Hyperon Spectrometer (HypTPC)
+ KURAMA @ K1.8 beamline





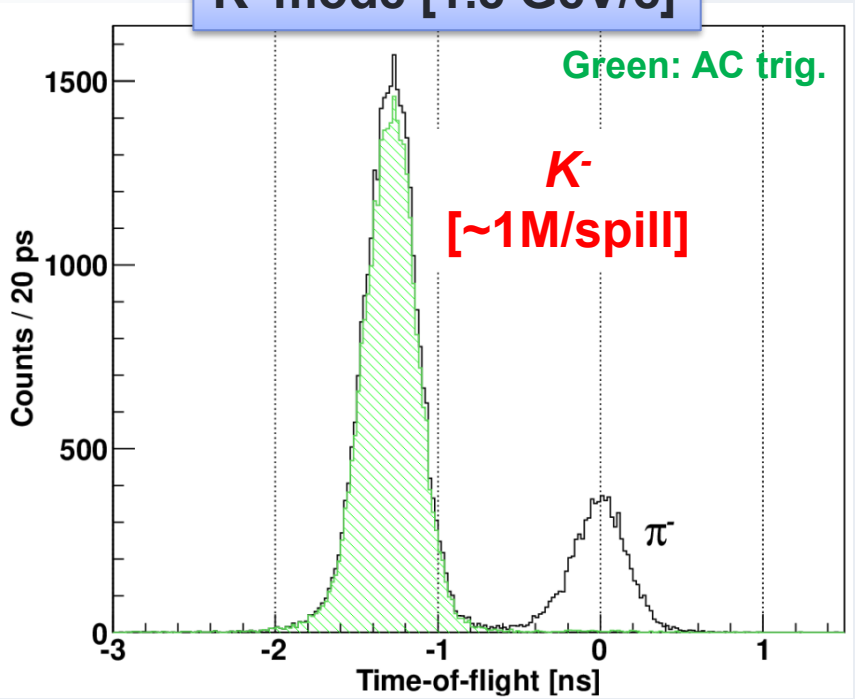
- Baryon spectroscopy [J-PARC E42] done in 2021
- Cusp spectroscopy [J-PARC E90] will be run in 2027?

Covered by Tanida-san's talk.

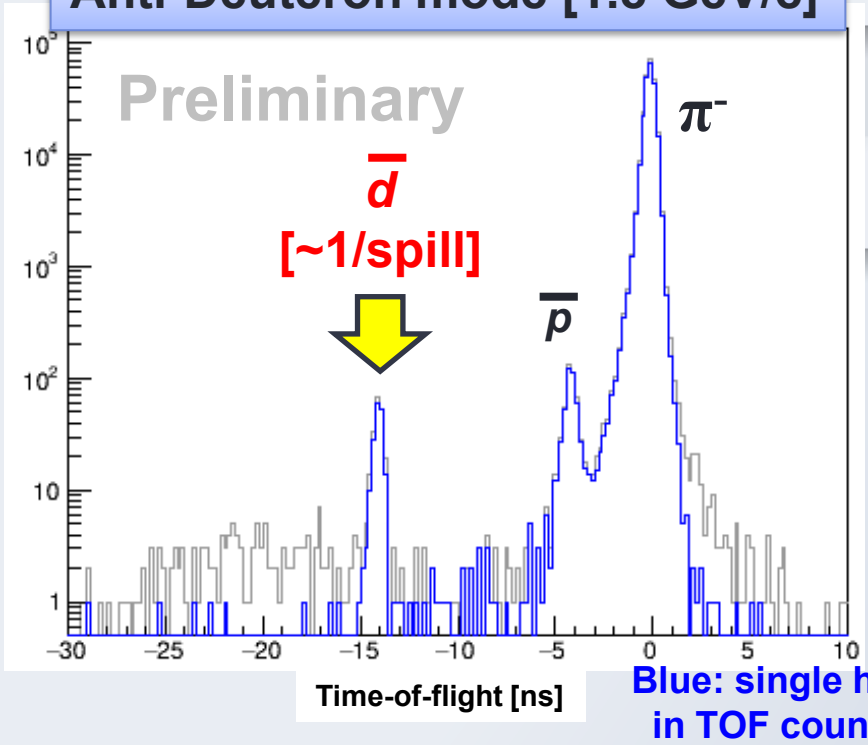
Future prospect and collaboration

Various beam particles in K1.8

K^- mode [1.8 GeV/c]



Anti-Deuteron mode [1.8 GeV/c]



Blue: single hit in TOF counter

- Separated beams of e, μ, π, K, *p* up to ±1.8 GeV/c
- In 2025, we succeeded in extracting $\bar{d}$ beams at 1.3, 1.5, and 1.8GeV/c
  -> new idea/experiment are welcome

HEF Extension project

K1.8BR (~1.0 GeV/c, K)

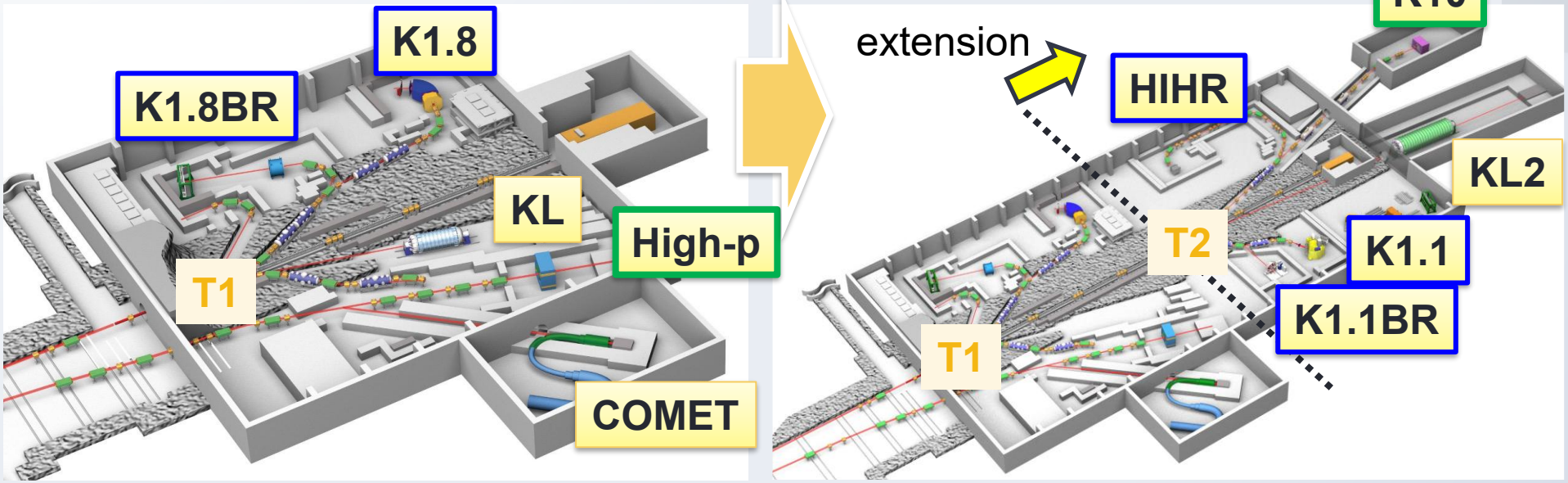
Kaonic atom / nuclei,
lifetime measurement

K1.8 (~1.8 GeV/c, K)

S=-2 hypernuclei

High-p Meson properties in nuclei

K10 Exotic hadron spectroscopy



HIHR (~2 GeV/c, π)

Precise Λ hypernuclear spectroscopy

K1.1/K1.1BR (~1.2 GeV/c, K)

S=-1 physics, gamma-ray spectroscopy

HEF-EX allows us to extend accessible physics and run in parallel w/ twice beam lines

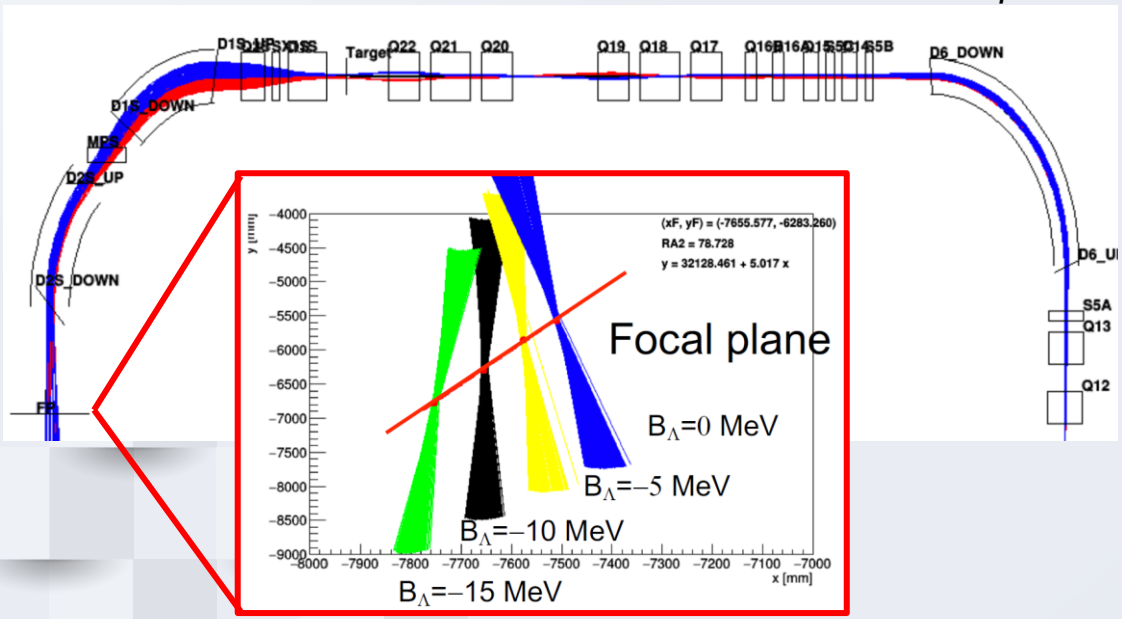
Λ Hypernuclear spectroscopy at HIHR

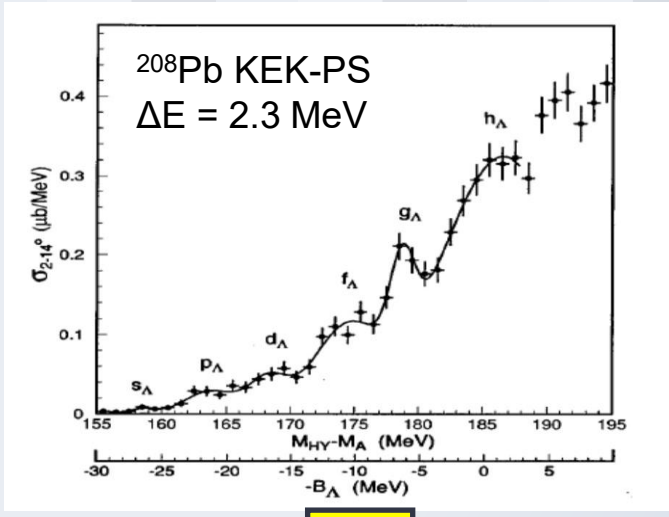
Reaction spectroscopy with sub-MeV resolution is essential for hypernuclear study

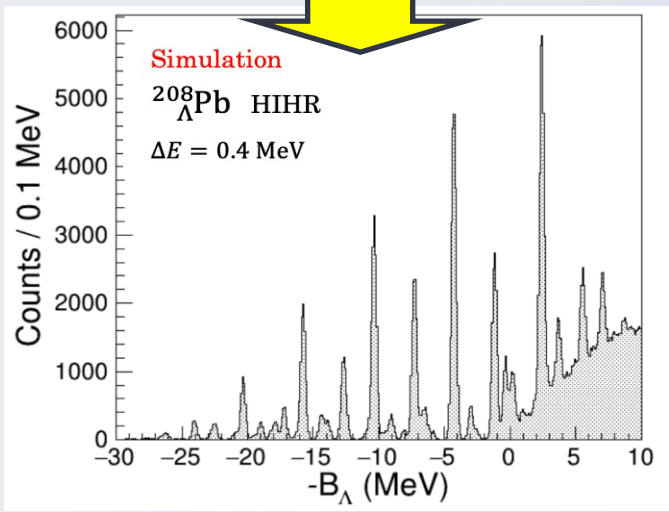
HIHR: Dispersion-matching beam line

- **0.4 MeV resolution**
- **pion beam intensity = 10^8/spill**
  (100 times higher than KEK-PS)

K. Miwa talk at HDex Workshop 2023







Clear separation at HIHR

Re-organizeation of Collaboration



URL: https://www.rcnp.osaka-u.ac.jp/~jparchua/en/index.html

Discussion was started based on Hadron hall User Association (HUA) for (potentially) newcomer to:

- **joining planed exp.**
- **support for new proposal**
- **access to existing data set**

Announcement will be made in near future.
Please contact us if you are interested in.

Summary

Many experiments were conducted at the J-PARC K1.8 beamline for hyperon-bound systems.

→ Study of hyperon-nucleon interaction

- **Exp. for S=-1 system**
  - **Hyperon scat. exp., gamma-ray spectroscopy**
- **Exp. for S=-2 system**
  - **Reaction spectroscopy, emulsion, X-ray spectroscopy**

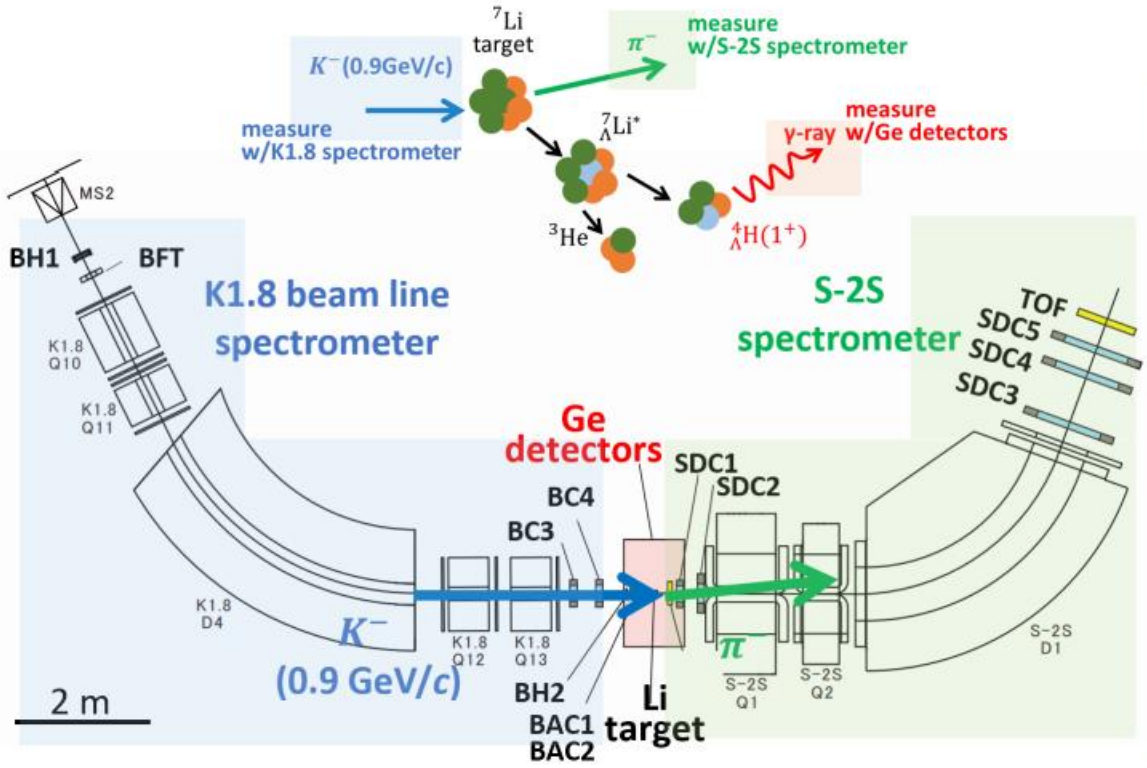
Future:

- **anti-d beam at K1.8 beamline (new ideas are welcomed)**
- **Hadron hall extension project**
- **Hadron hall corroboration re-arrangement**

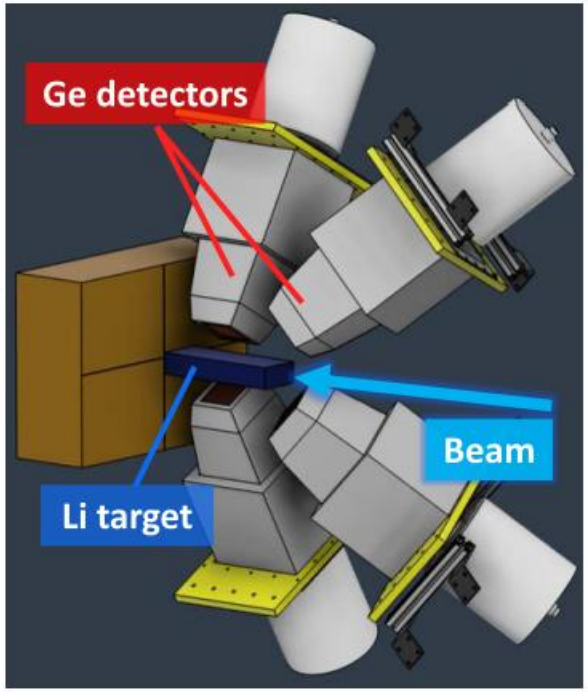
Backup

Experimental setup at J-PARC K1.8 beam line

(K^-, π^-) reaction is identified by K1.8, S-2S

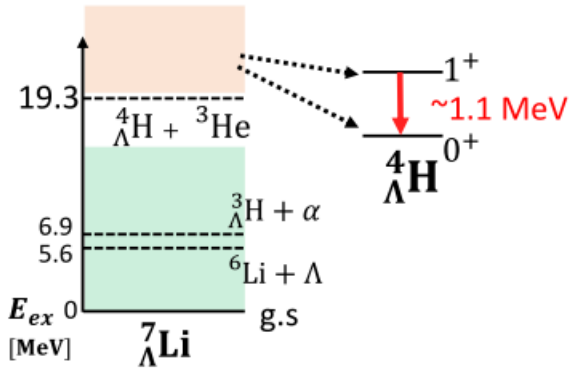


Ge detector array (half)

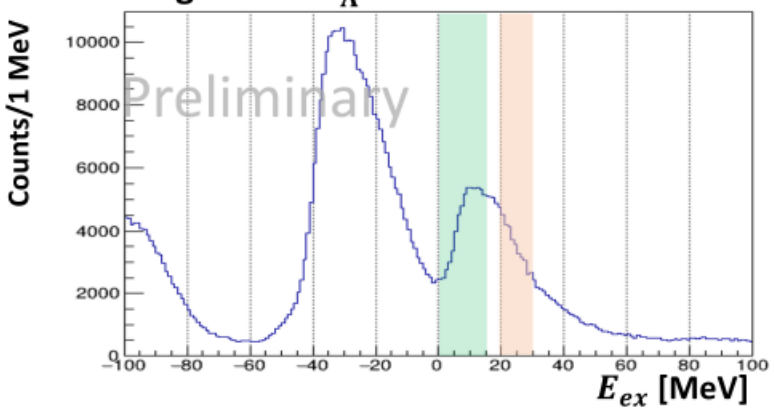


Mass-gate dependence of γ-ray spectra

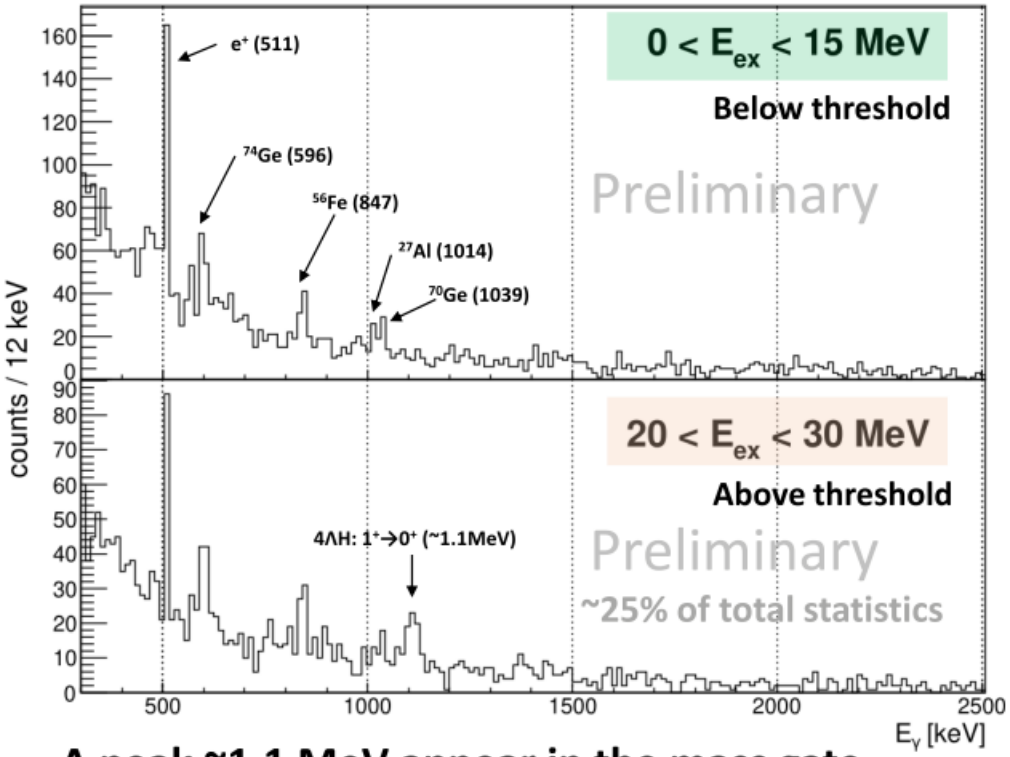
Decay thresholds of $^{7}_{\Lambda}$Li



Missing Mass of $^{7}_{\Lambda}$Li

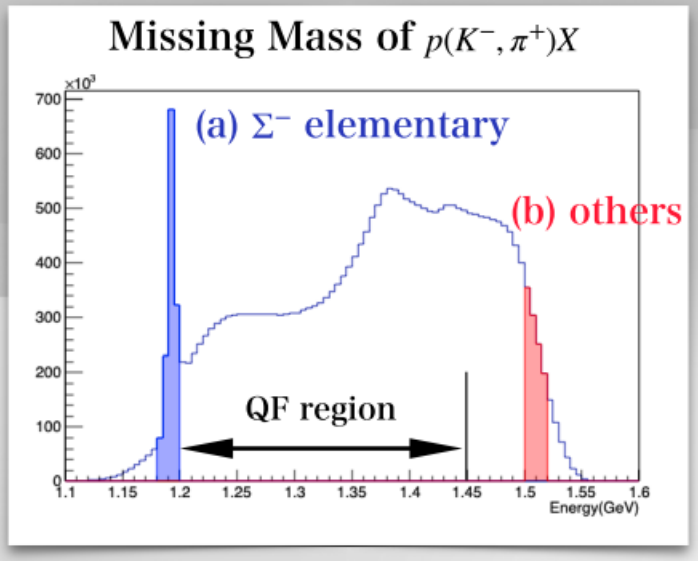


Mass gated γ-ray spectra



A peak ~1.1 MeV appear in the mass gate above the $^{4}_{\Lambda}$H threshold.

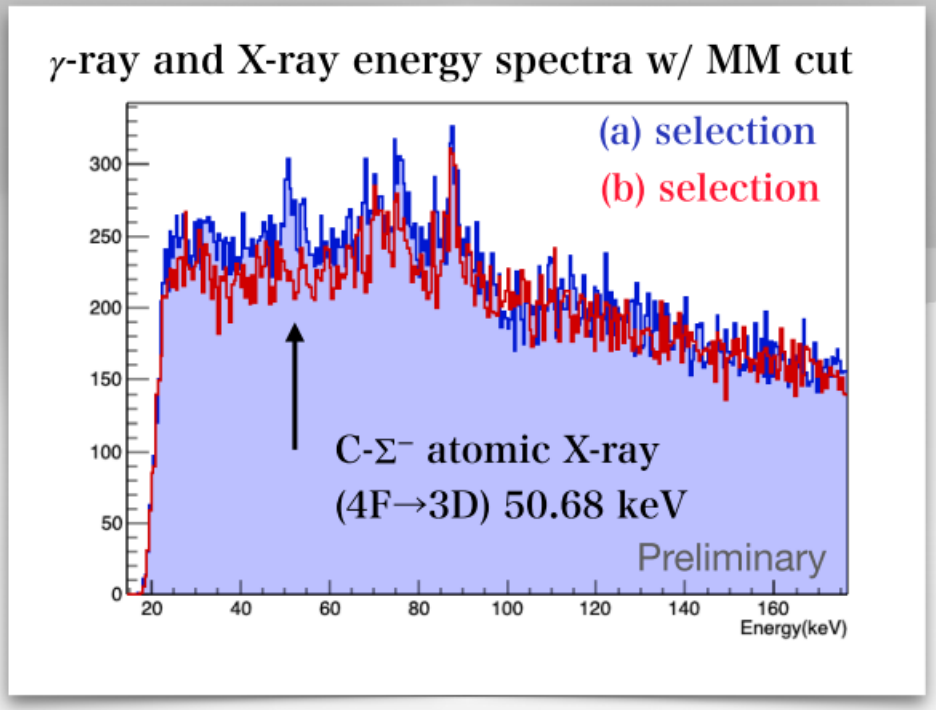
Σ^--C atomic X-ray measurement w/ Spectrometers coincidence

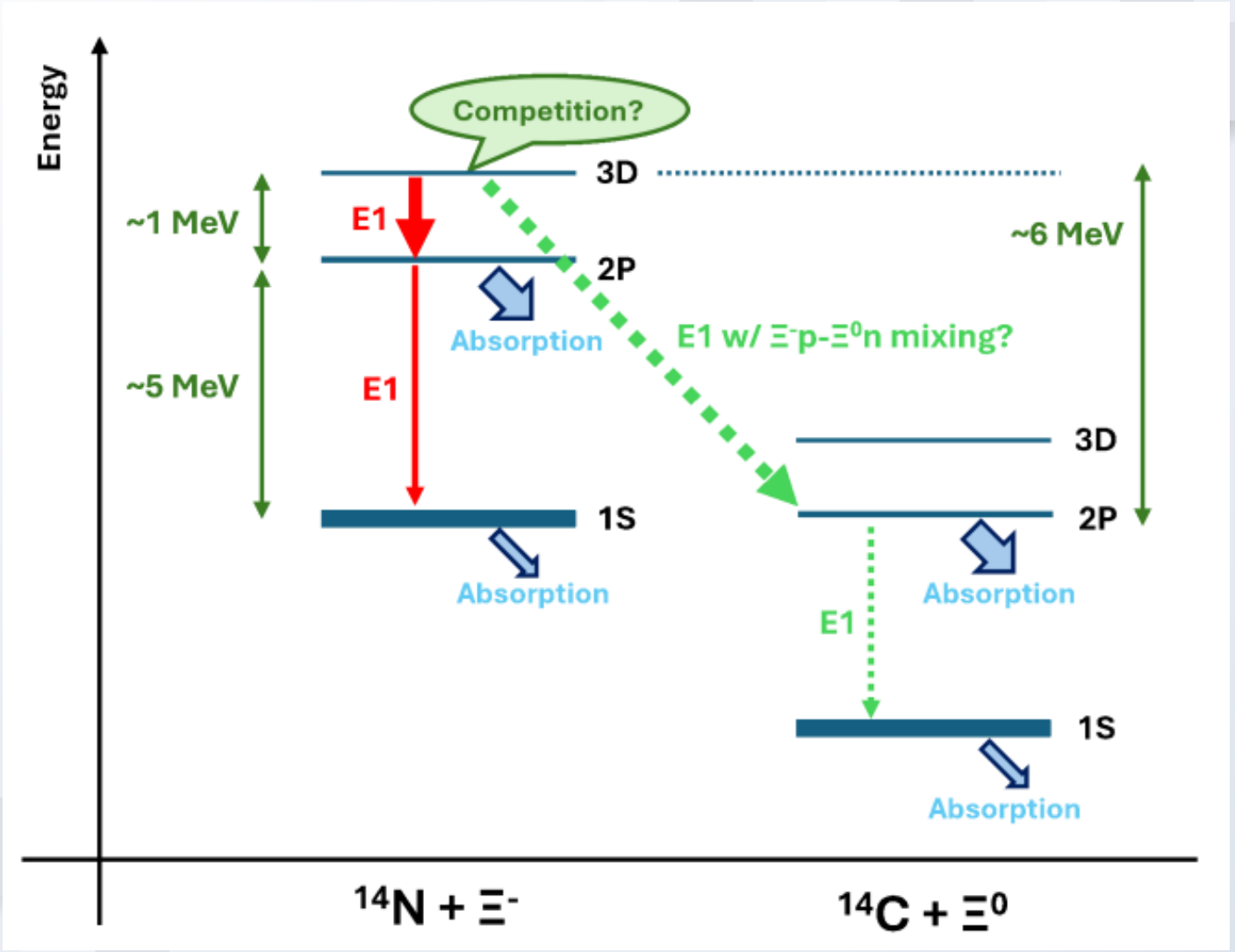


(a) $p(K^-, \pi^+)\Sigma^-$: 1.18 GeV< MM < 1.20 GeV

(b) others : 1.50 GeV< MM < 1.52 GeV

target : CH [AFT]




Energy
Competition?
3D
~1 MeV
E1
2P
~6 MeV
Absorption
E1 w/ Ξ⁻p-Ξ⁰n mixing?
~5 MeV
E1
3D
1S
2P
Absorption
Absorption
E1
1S
Absorption
$^{14}N + \Xi^-$
$^{14}C + \Xi^0$